EFFECTS OF PROCESS VARIABLES ON DIMENSIONAL CONTROL OF COLD DRAWN 1526 GRADE STEEL TUBING

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EFFECTS OF PROCESS VARIABLES ON

DIMENSIONAL CONTROL OF COLD DRAWN 1526

GRADE STEEL TUBING

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Abstract:

Dimensional control is a major concern for producers of cold drawn steel tubing. Producing out of tolerance material can lead to increased costs and manufacturing time. Improving dimensional control leads to better process control and may provide a competitive advantage. The effects of the drawing die entry angle, percent area reduction, and drawing speed on the as drawn dimensions of steel tubes were examined. The minimum, maximum, average, and standard deviation of the resulting outer diameters and wall thicknesses were determined. The deviation of the measurements from target values was also analyzed.

It was shown that both die entry angle and percent area reduction affect the standard deviation of the as drawn outer diameter and wall thickness. The measurement deviation from target dimensions was shown to be a function of percent area reduction. It was also shown that increasing percent area reduction caused the as drawn outer diameter dimensions to be increasingly biased less than the target.

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α	-Die angle
β	-Mandrel angle
σ	-Drawing stress
σ'_y	-Plane strain yield strength
h_a	-Wall thickness after drawing
h_b	-Wall thickness before drawing
μ_1,	-Coefficient of friction between tube and die
μ_2	-Coefficient of friction between tube and mandrel
m	-Shear factor
τ	-Tangential stress
σ_o	-Uniaxial tension yield strength
R_i	-Inner radius
R_o	-Outer radius before drawing
R_{of}	-Outer radius after drawing
OD_f	-Outer diameter after drawing
ID_f	-Inner diameter after drawing
OD	-Outer diameter before drawing
ID	-Inner diameter before drawing

CHAPTER I

INTRODUCTION

1.1 Description of Cold Drawn Tubular Products

Cold drawn tubing is used in many industries including power generation, oil and gas, chemical processing, automotive, and mining. Both welded and seamless tubing which has been cold drawn may be preferred over hot formed tubing for many reasons including increased yield strength, tensile strength, and hardness, tight dimensional tolerances, and smooth surface finish.

Cold drawing can also be used to form shapes such as hexagons, squares, or tubes with wall thickness to diameter ratios which would be impossible to manufacture in by welding alone. Additionally, cold drawing can be employed to produce uncommon sized tubing which would not warrant purchase of expensive roll tooling sets and large quantities of strip steel.

Another advantage of a cold drawing operation is its flexibility. A finished cold drawn tube can be manufactured from a multitude of beginning sizes and conversely one starting size tube can easily be cold drawn to numerous finished sizes. This allows manufacturers to produce a large number of products with reduced inventory and lead times.

With increasing efforts to improve efficiency and reduce costs, designers continuously request tighter dimensional tolerances from manufacturers of cold drawn tubing. Tighter dimensional tolerances allow for reduction or even elimination of subsequent machining processes such as boring, honing, or grinding thus greatly reducing costs and manufacturing time.

These factors increase the importance of a tubing manufacturer having in depth knowledge of the cold drawing process and its effects on the finished product. Variables under the control of the manufacturer such as tooling design and total area reduction directly affect the mechanical and dimensional properties of the finished tube [1].

The purpose of this research is to develop a better understanding of the relationship between controllable process variables and their effect on the as drawn dimensions of cold drawn low carbon steel tubing. Die entrance angle, area reduction, and draw speed are independently varied and tested in an industrial cold drawing facility. The resulting dimensional effects are evaluated and conclusions concerning the effects of each variable are made.

1.2 Types of Cold Drawing Operations

Cold drawn tubing is manufactured by pulling a tube through a die, sometimes over a plug or mandrel. The angle of the die opening is known as the die angle and is shown as α in figure 1-1. The type of drawing operation is characterized by the presence, or lack of, a mandrel and its type [1]. Tube sinking, as shown in figure 1-1, refers to drawing without the use of a mandrel.

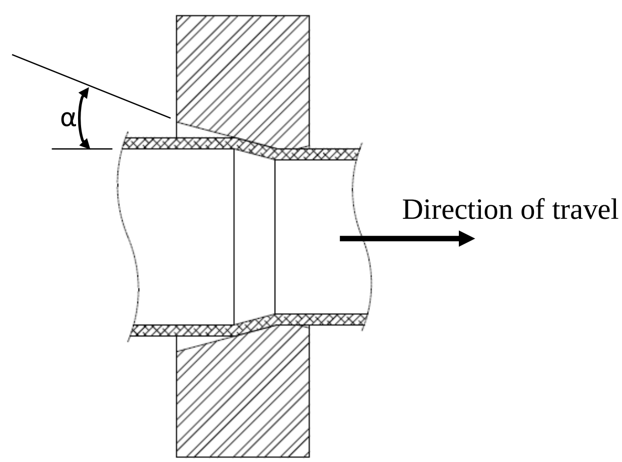


Figure 1-1 Tube Sinking Operation

This operation offers little control over the inner diameter of the tube. Sinking operations are generally performed when only a reduction in outer diameter is desired and the inner diameter is not critical. Tube sinking is also commonly used as the first pass in a multi-pass drawing operation in order to reduce the outer diameter without a reduction in wall thickness. Subsequent passes frequently employ a mandrel in order to control the inner diameter or wall thickness of the finished tube.

Tube drawing operations utilizing internal mandrels are characterized by the interaction between the mandrel and the tube during the drawing process. The three types of mandrel drawing are:

1. Fixed mandrel
2. Floating mandrel
3. Moving mandrel

In a fixed mandrel drawing operation as depicted in figure 1-2, the mandrel is attached to a rod which is loaded into the back of the tube.

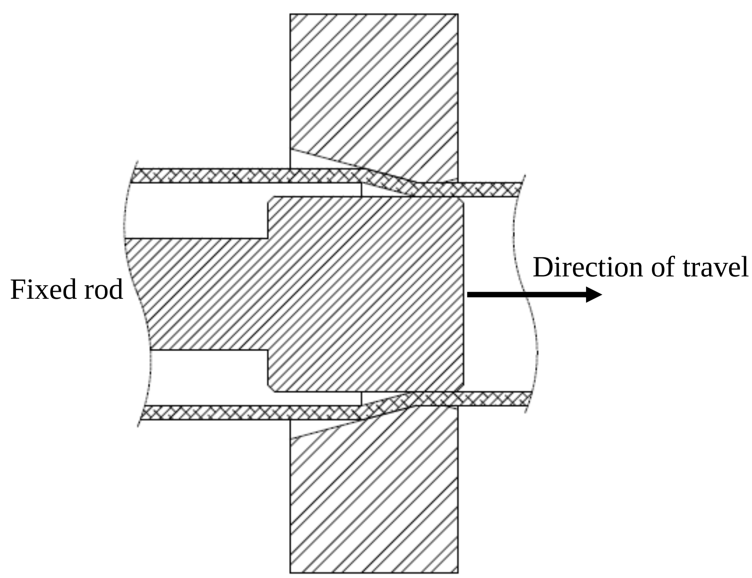


Figure 1-2 Fixed Mandrel Operation

The rod is mechanically, hydraulically, or pneumatically held in place throughout the drawing cycle. This keeps the mandrel in place as the tube is pulled through the die and over the mandrel. In this type of operation the mandrel can either be cylindrical or tapered.

Figure 1-3 depicts a floating mandrel configuration which requires a tapered mandrel. The mandrel angle is shown as β in figure 1-3. The geometry of the die and mandrel act to keep the mandrel in position during drawing. A floating mandrel operation removes the need for a mandrel rod thus making it possible to continuously draw long coils of tubing.

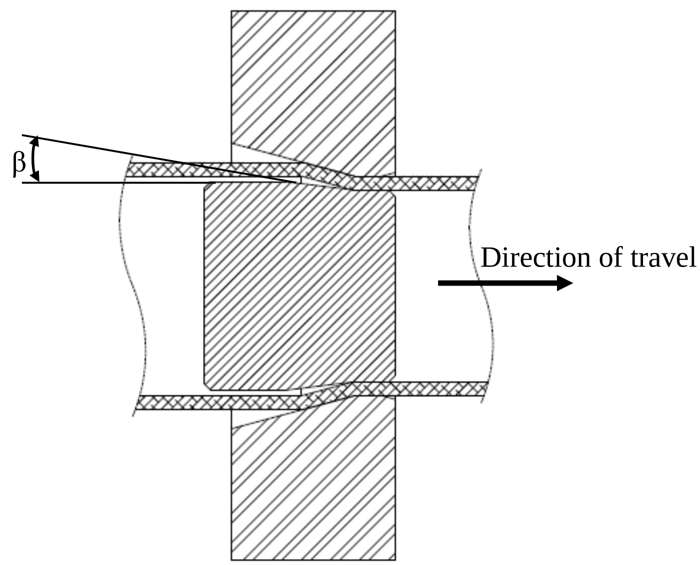


Figure 1-3 Floating Mandrel Operation

In a moving mandrel configuration, as shown in figure 1-4, a cylindrical mandrel equal or greater in length than the tubing being manufactured is loaded into the tube and passes through the die with the tube.

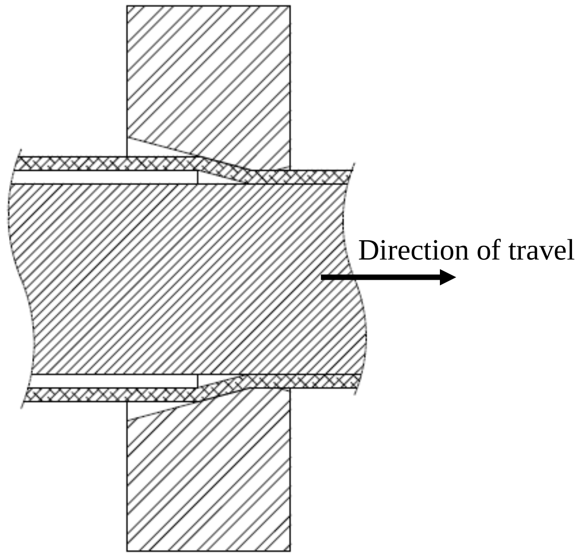


Figure 1-4 Moving Mandrel Operation

In this configuration the movement of the mandrel with the tube minimizes friction losses between the tube and mandrel as compared to either fixed or floating mandrel operations. The finished tube must be rolled in order to unload the mandrel from the finished tube. The unloading operation frequently causes an increase in the outer diameter of the finished tube. [2]

CHAPTER II

REVIEW OF LITERATURE

2.1 Review of Previous Literature

Hoffman and Sachs [3], using the slab method which assumes homogenous deformation, showed that in a drawn over mandrel operation for situations in which the wall thickness reduction is much greater than the outer diameter reduction the drawing operation can be assumed to have plane-strain conditions. Equation 2-1 describes the drawing stress assuming plane-strain conditions and a cylindrical mandrel, σ_y' is the yield strength of the material in plane strain and h_b and h_a are the wall thickness of the tube before and after drawing respectively.

$$\sigma = \sigma_y' \frac{1+B}{B}\left[1 - \left(\frac{h_a}{h_b}\right)^B\right] \tag{2-1}$$

Where

$$B = \frac{\mu_1 + \mu_2}{\tan \alpha}$$

Avitzur [4] utilized an upper bound approach to define the drawing stress in a more complete manner than Hoffman and Sachs. This method allows inclusion of the nonuniform, or redundant, shear deformation. Avitzur described the total drawing stress as being comprised of 3 components:

1. Ideal deformation stress, that required to cause dimensional change
2. Stress necessary to overcome the friction between the tube and the tools

3. Non ideal deformation stress, that which is required to overcome redundant shear deformation.

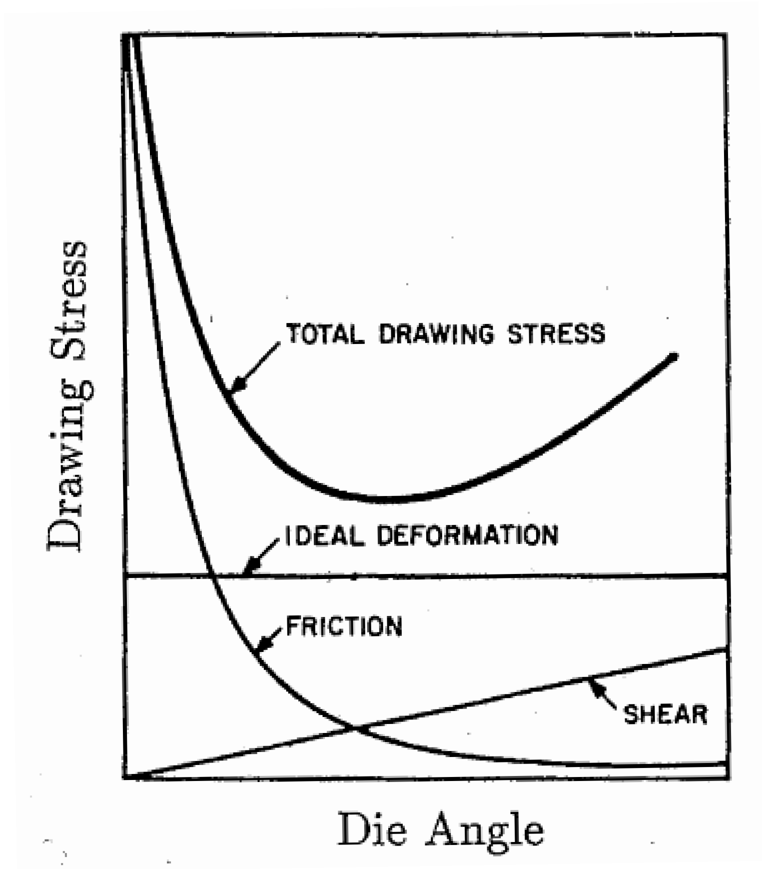


Figure 2-1: Components of Total Drawing Stress [4]

Figure 2-1 shows how the components of the total drawing stress vary with the die angle. The stress necessary for ideal deformation is independent of the die angle, the friction component of drawing stress is maximum at 0˚ and decays exponentially with increasing die angle. The redundant shear component displays a positive linear relationship with die angle.

To demonstrate the effects of reduction on drawing stress Avitzur employed an upper bound approach to calculate drawing stress. Figure 2-2 displays the dependence of drawing stress on diameter reduction and die angle for different values of shear factor m which is defined by equation 2-2.

$$m = \frac{\sqrt{3}\tau}{\sigma_0} \tag{2-2}$$

A value of m=0 indicates no friction while m=1 indicates the maximum possible friction.

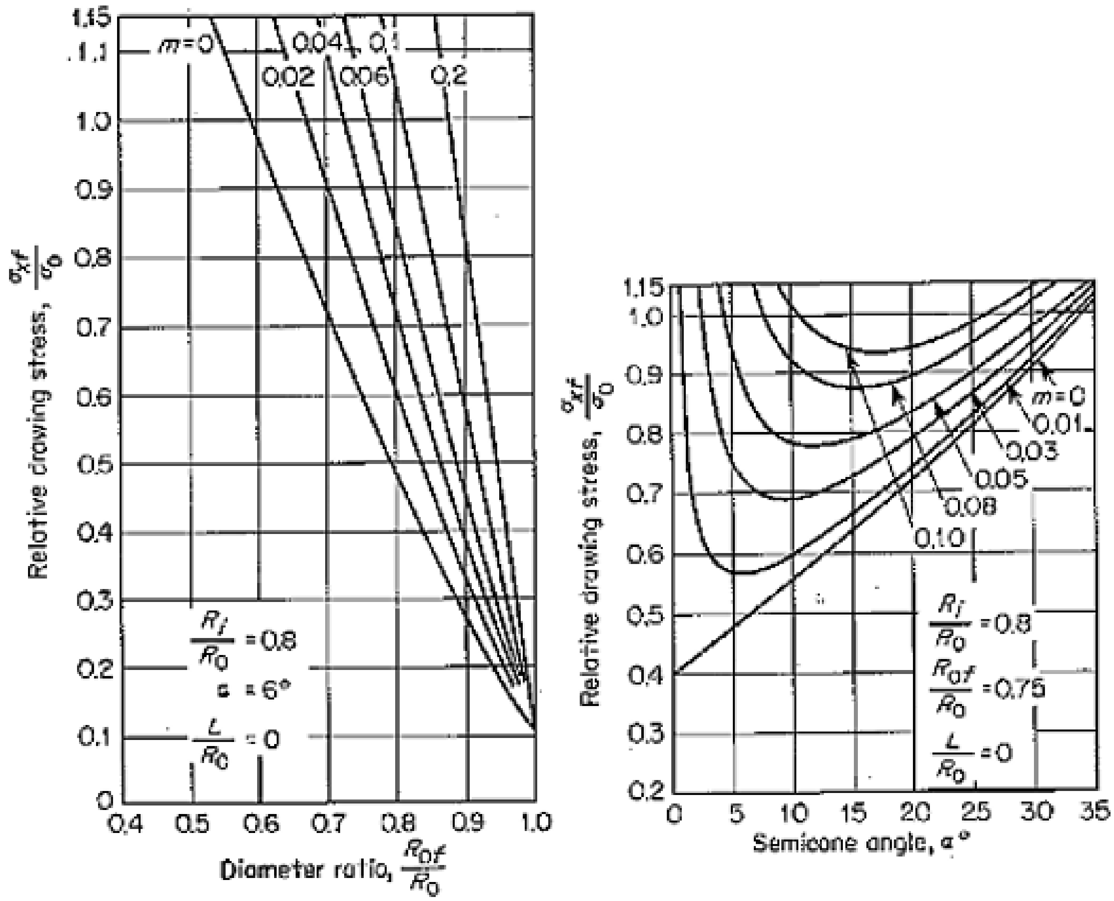


Figure 2-2: Dependence of Drawing Stress on Diameter Reduction and Die Angle [2]

It was shown that higher diameter reductions increase the drawing stress. Die angle showed a parabolic relationship with drawing stress indicating that a particular drawing operation will have some optimum die angle resulting in the lowest drawing stress represented by the minimum sum of the friction and redundant shear components. The optimum die angle can be approximated using equation 2-3:

$$\alpha \approx \sqrt{\frac{3}{2} m \frac{\ln(R_o/R_{of})}{1-(R_i/R_o)^3}} \quad (2\text{-}3)$$

Lee [5] explored automated optimum die design for use in the production of AISI 1045 grade steering shafts; the initial die design had resulted in fracture of the steering shafts during drawing. A die optimization program was developed which combined a parametric die model and finite element analysis of the drawing operation. The program used an iterative process to alter the die design. The die design was deemed optimum when the stress distribution throughout the cross section reached a minimum value. Figure 2-3 shows the 16 iterated die designs and a comparison between the initial and optimized shape, iteration 12 was deemed optimum. The computed die was subsequently used in production and steering shafts were successfully drawn without fracturing.

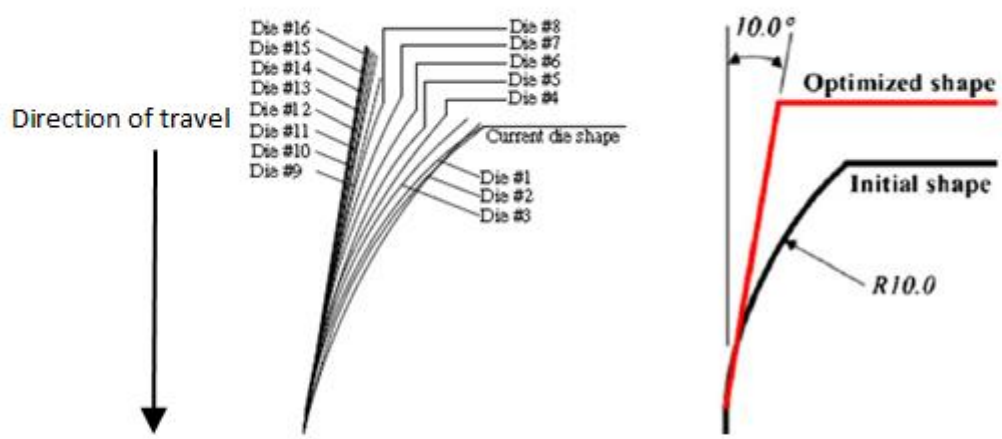


Figure 2-3: Iterative Solution of Optimum Die Angle [5]

Chapman [6] investigated the effects of process variables on the residual stress state in cold drawn copper tubes. Finite element analysis was used to determine the residual stress distributions due to varying die angle, mandrel angle, and area reduction; thermal effects were also investigated. Area reductions of 10.9% and 37.1% along with die angles of 15˚, 17.5˚, 20˚, and 22.5˚ were examined. Mandrel angles were 2.5˚, 5˚, and 7.5˚ less than the die angles. All simulations were run utilizing the finite element analysis software ABAQUS. Isothermal simulations were run for all reduction and angle combinations while temperature dependent simulations were run for 10.9% and 37.1% reductions with a die angle of 15˚ and a mandrel angle of 7.5˚. Radial residual stresses were neglected due to their small magnitude compared to the circumferential and longitudinal stresses. It was determined that speed and temperature rise during drawing shared a positive relationship. Temperature did not show any effect on the residual stress distribution for the variable ranges investigated. It was determined that the die and mandrel angles had a significant effect on the drawing and residual stress. It was observed that the magnitude of the residual stresses was generally reduced as the mandrel angle approached the die angle.

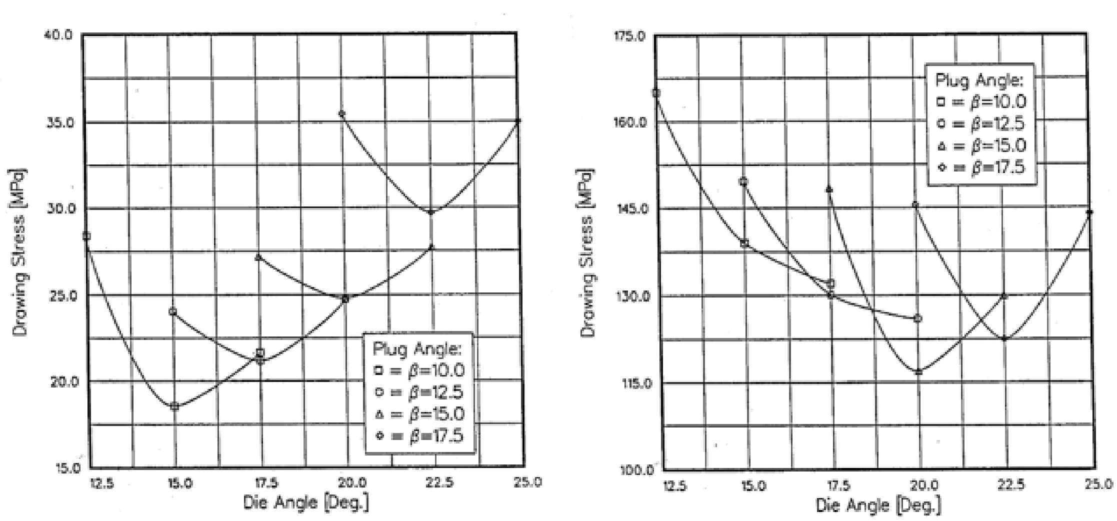


Figure 2-4: Effect of Die and Mandrel Angle on Drawing Stress, Left-10.9% Reduction, Right-37.1% Reduction [6]

Using figure 2-4 the relative effect of the die and mandrel angles can be determined. The relative effect of the tooling angles can be defined as the variation of the drawing stress divided by the average stress for a given mandrel angle. Table 2-1 gives the relative effect for the four mandrel angles at both 10.9% and 37.1% reduction.

		Variation (MPa)	Average (MPa)	Effect	
Mandrel Angle (Deg)	10.0	10.0	22.7	44.1%	10.9%
	12.5	3.5	23.5	14.9%	
	15.0	2.5	26.5	9.4%	
	17.5	5.0	33.3	15.0%	
	10.0	35.0	145.0	24.1%	37.1%
	12.5	25.0	135.0	18.5%	
	15.0	32.0	131.3	24.4%	
	17.5	22.5	137.5	16.4%	

Table 2-1: Relative Effect of Die and Mandrel Angle on Drawing Stress

For a mandrel angle of 10˚, the relative effect of the changing die angle on the drawing stress was observed to be greater at 10.9% area reduction than at 37.1% area reduction. For all other mandrel angles, the relative effect of the changing die angle was observed to be greater at 37.1% area reduction.

Béland [7] optimized the tool design of a combined sinking and fixed mandrel drawing operation for 6063 aluminum tubes. In this type of process the tube first passes through the sinking die and then immediately passes through another die and over the mandrel. Figure 2-5 shows the die and mandrel layout.

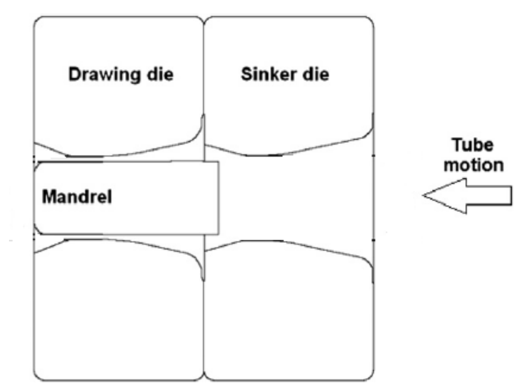


Figure 2-5: Combined Sinking and Fixed Mandrel Drawing

Using finite element analysis the existing two step operation was modeled. The geometry of both the sinking and drawing die was optimized to allow the operation to be performed in one step. Die optimization was based on reducing the total drawing stress thus preventing fracture of the tube during drawing. In this case, the optimum die angle resulting in the lowest measured drawing force was found to be 10˚. The drawing force displayed the expected parabolic relationship with the die angle as previously shown by Avitzur [4].

Xu [8] developed a mandrel design which improved the wall thickness tolerance of cold drawn rectangular 6061 aluminum tubes. A mandrel design which incorporated a raised boss on the outside corners was proposed in order to increase the reduction and improve the wall thickness tolerances in these areas. Figure 2-6 shows a comparison of the two mandrels.

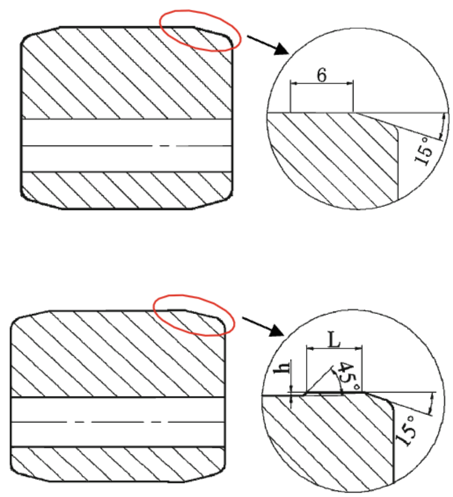


Figure 2-6: Comparison of Rectangular Mandrels, Top-Existing, Bottom-Proposed [8]

Finite element analysis was conducted with varying values of the boss height *h* and boss length *L* until the wall thickness variation reached a minimum. Based on FEA it was found that the new mandrel decreased the wall thickness variation and increased the necessary drawing force.

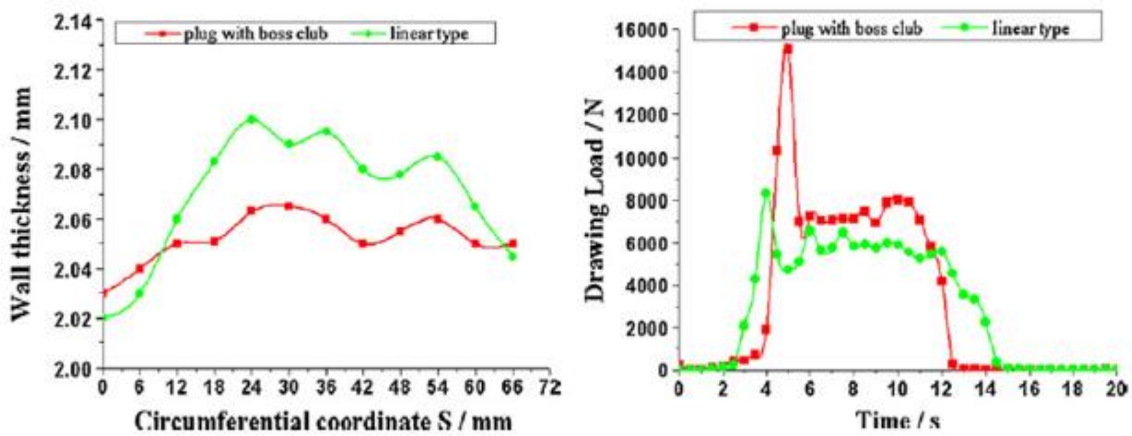


Figure 2-7: Effect of Rectangular Mandrels on Wall Thickness and Drawing Force [8]

Simulation results were verified through experimentation. Wall thickness measurements of rectangular tubes manufactured with each plug were taken and compared as shown in Table 2-2.

Measurement #	Linear Mandrel	Boss Mandrel
	t (mm)	t (mm)
1	2.02	2.03
2	2.05	2.04
3	2.07	2.06
4	2.06	2.05
5	2.05	2.03
6	2.04	2.04
7	2.08	2.03
8	2.06	2.05
9	2.05	2.05
10	2.04	2.04
Minimum	2.02	2.03
Maximum	2.08	2.06
Average	2.05	2.04
Std Dev	0.016	0.010

Table 2-2: Comparison of Rectangular Tube Wall Thickness Measurements

2.2 Summary and Research Objective

The majority of previous work has been focused on optimizing die and mandrel design with emphasis on the drawing stress encountered by the tube. For a manufacturer with a diverse portfolio of customers developing an optimized die for each item is impractical. Additionally, in many instances the drawing stress encountered by the tube is not high enough to warrant concern and many products require a stress relieving operation after cold drawing thus removing the concern of residual stresses after drawing.

In these cases, the manufacturer is likely most concerned with final product dimensions. This research aims to address those concerns and remedy the current lack in the literature of a comprehensive investigation of the dimensional effects caused by varying die angles, draw speeds, and percent reductions. Efforts are focused on fixed mandrel drawing of 1526 grade steel using conical dies and cylindrical mandrels.

CHAPTER III

METHODOLOGY

3.1 Description of Equipment and Material

The goal of this research was to determine the effects of die entry angle, percent area reduction, and draw speed on the as drawn dimensions of 1526 grade steel tubes. Experiments were conducted on a rack and pinion style draw bench. A representative schematic of the draw bench is shown in Figure 3-1.

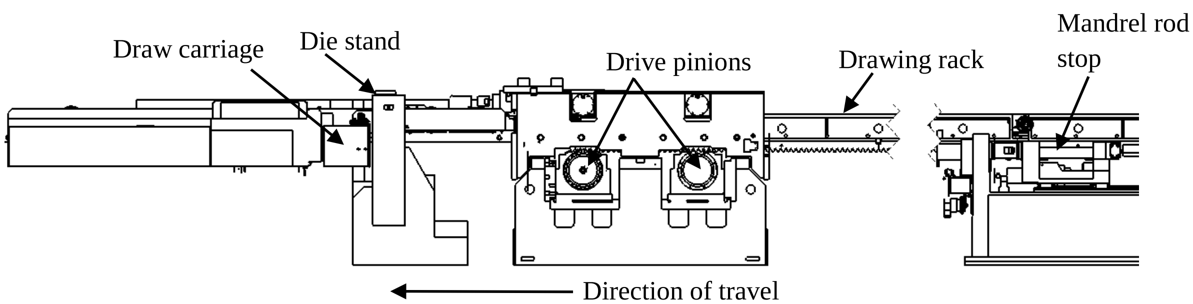


Figure 3-1: Rack and Pinion Style Draw Bench

The machine consisted of two drive pinions powered by AC motors which drive a horizontal rack attached to the draw carriage. The draw carriage holds a hydraulic powered gripper block which holds the leading edge of the tube and pulls it through the die stand which holds the die. During the drawing operation, the mandrel is held inside the die by a steel rod which is fixed in place against a stop. The tubes available for drawing were manufactured by electric resistance welding of 1526 grade steel strip and were 3.500in in outer diameter with an average wall thickness of 0.253in. Two different heats of material were used; Table 3-1 provides a mass basis chemical composition of each heat compared to the ASTM requirement [9].

	Heat 1	Heat 2	ASTM Specification
C	0.260	0.260	0.22 – 0.29
Mn	1.250	1.310	1.10 – 1.40
P	0.008	0.010	0.040 max
S	0.001	0.001	0.050 max
Si	0.170	0.170	0.10 – 0.20
Ni	0.030	0.030	–
Cr	0.030	0.040	–
Mo	0.010	0.010	–
Cu	0.080	0.080	–
Al	0.030	0.030	–

Table 3-1: Chemical Composition of Heats

The dies used during drawing were comprised of a two part design consisting of an inner conical carbide working surface, or nib, and an outer steel casing. The carbide nib is held in place by an interference fit between it and the case. Figure 3-2 displays a general die schematic.

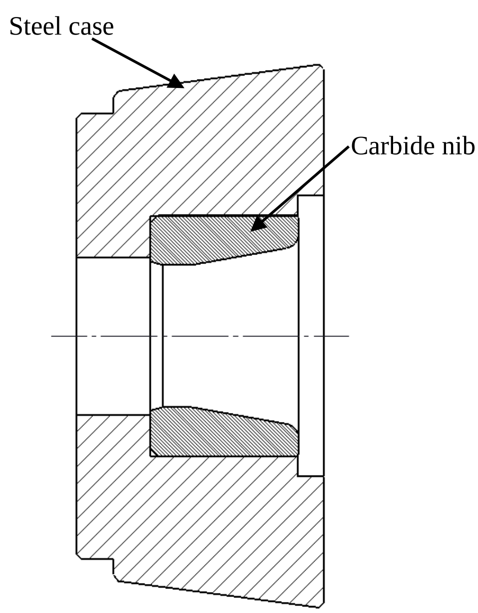


Figure 3-2: Drawing Die Schematic

The mandrels used during drawing consist of a carbide nib fixed in place on a steel body, or shank, by a cap and bolt; the shank is attached to a mandrel rod via a threaded attachment. Figure 3-3 shows a mandrel schematic.

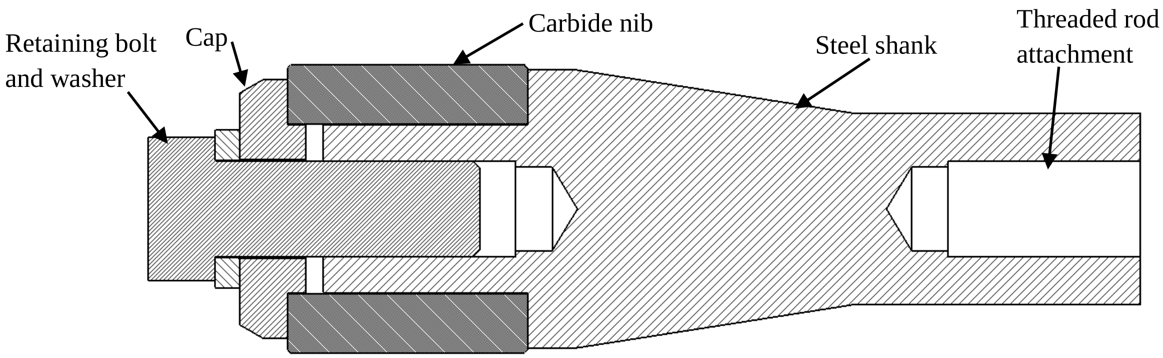


Figure 3-3: Drawing Mandrel Schematic

Before drawing, the tubes were processed through a typical cold drawing preparation process [2]. The tubes were heated above 1650 ˚F and slow cooled in a controlled inert atmosphere to normalize the grain structure of the electric resistance seam weld. After heat treatment the tubes were treated in a multistep chemical process to allow the application of an industrial soap drawing lubricant. Immediately before drawing, the leading end of each tube was formed by a hydraulic powered push pointer in order to allow the leading end of the tube to pass through the die and be grasped by the drawing carriage. Figure 3-4 depicts a flow chart of the steps involved in the pretreatment and cold drawing process.

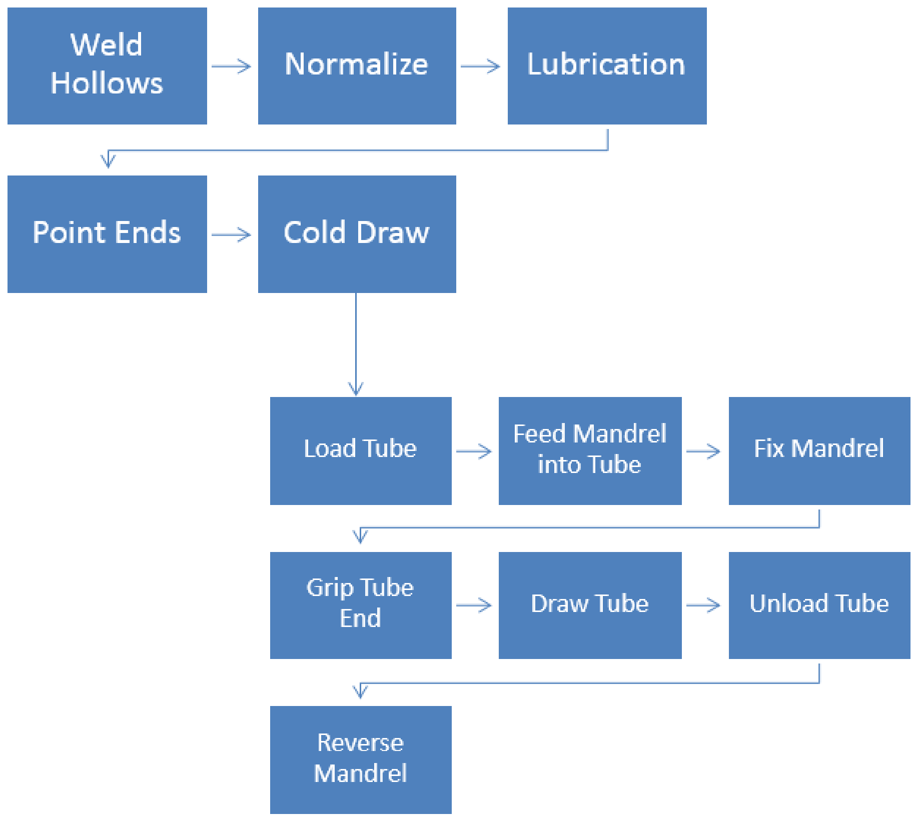


Figure 3-4: Flow Chart of Pretreatment and Cold Draw Process

3.2 Description of Experiment

The goal of this research was to investigate the effects of three variables on the resulting dimensions of cold drawn tubing: die angle, drawing speed, and percent area reduction. As such, it was important that any experiments be conducted in a manner that would allow each of the three variables to be evaluated independently. In order to isolate the effects of each variable under investigation a matrix of experiments was devised which allowed independent variation of each variable. Table 3-2 below illustrates the resulting variable combinations which were investigated.

	Angle				
Area Reduction		**10˚**	**15˚**	**20˚**	**25˚**
	15.5%	50ft/min	50ft/min	50ft/min	50ft/min
		150ft/min	150ft/min	150ft/min	150ft/min
	20.2%	50ft/min	50ft/min	50ft/min	50ft/min
		150ft/min	150ft/min	150ft/min	150ft/min
	26.1%	50ft/min	50ft/min	50ft/min	50ft/min
		150ft/min	150ft/min	150ft/min	150ft/min
	34.9%	50ft/min	50ft/min	50ft/min	50ft/min
		150ft/min	150ft/min	150ft/min	150ft/min

Table 3-2: Matrix of Variable Combinations

Table 3-3 shows the target outer diameter and wall thickness resulting in the percent area reductions selected. Area reduction was calculated using equation 3-1.

$$Area\ Reduction = \left[1 - \frac{\left(OD_f^2 - ID_f^2\right)}{\left(OD^2 - ID^2\right)}\right](100) \qquad (3\text{-}1)$$

Area Reduction	Outer Diameter (in)	Wall Thickness (in)
15.45%	3.250	0.230
20.19%	3.200	0.220
26.12%	3.100	0.210
34.87%	2.875	0.200

Table 3-3: As Drawn Target Outer Diameters and Wall Thicknesses

Variable ranges were chosen based on current practices, mechanical limitations, and process limitations. Die entry angles were selected with care given to versatility and cost. For a fixed length, as the entry angle decreases the potential outer diameter reduction also decreases. At 10˚ the maximum difference in the incoming and as drawn diameters was approximately 0.625in. A small range of possible incoming tube sizes drastically reduces the versatility and therefore usefulness of the die. Conversely, a large entry angle increases the potential outer diameter reduction and therefore the versatility of the die. However, in order to maintain the strength and lifespan of the die it is necessary that the outer diameter of the carbide nib be increased as well; this results in an increase in tooling cost. At 25˚ the maximum difference in outer diameters was approximately 1.75in and the carbide nib diameter was 5.875in. This was 1in more than the 10˚ nib and resulted in a 30-50% price increase depending on vendor. Figure 3-5 shows the four nibs used during drawing.

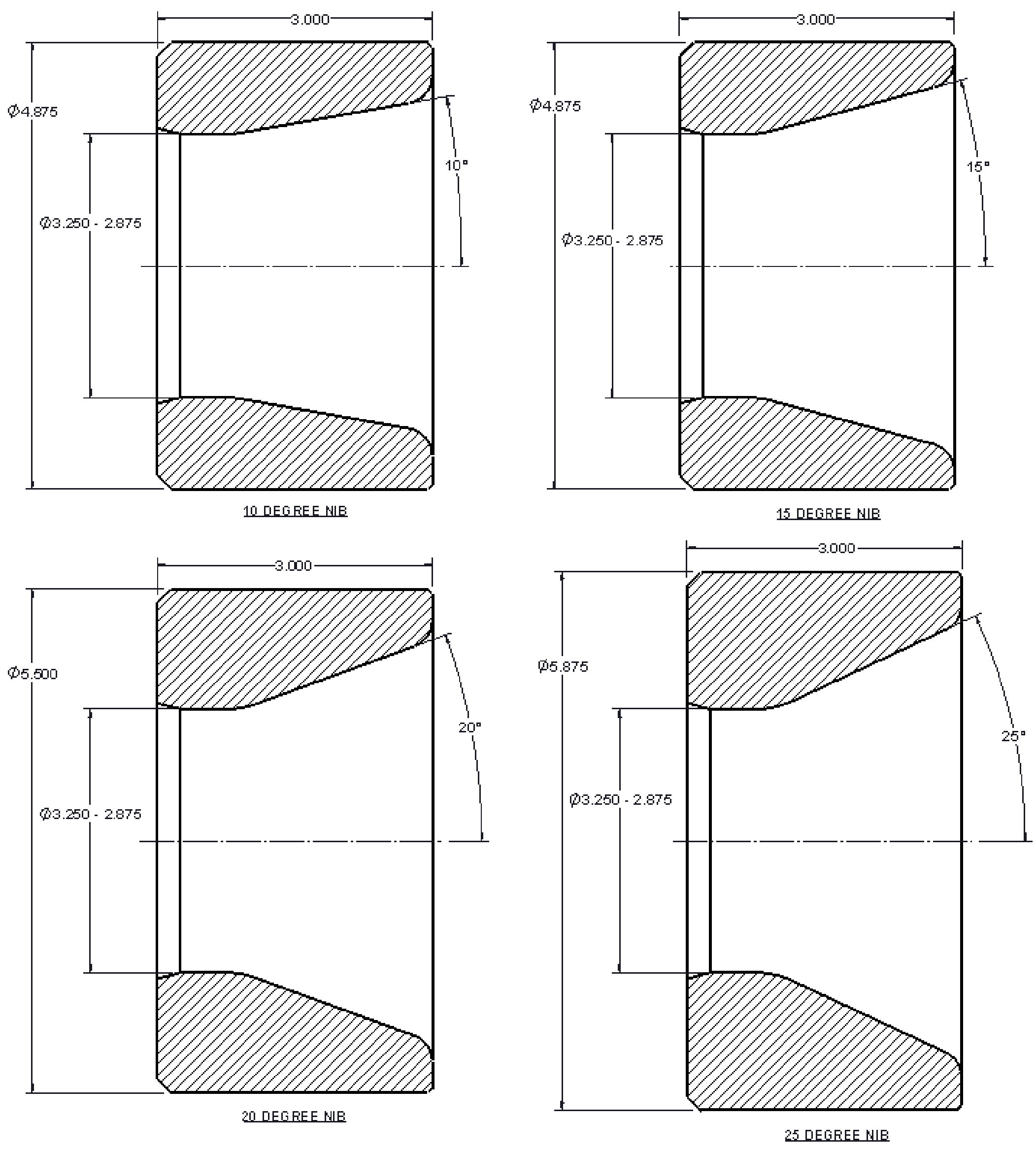


Figure 3-5: Details of Carbide Die Nibs

Percent area reductions were chosen with consideration given to the limits imposed by the die design and end use of the tubes. This research was conducted as part of a real world production process and the maximum reduction was therefore chosen to coincide with the finished size of the product the material was dedicated to: 2.875in outer diameter and 0.200in wall thickness. This required that the remaining reductions be chosen to incorporate outer diameters and wall thicknesses greater than 2.875in and 0.200in respectively. Additionally, it was important to consider the mandrel clearance available during each pass. Mandrel clearance is the available space between the outer diameter of the mandrel and the inner diameter of the incoming tube. Insufficient clearance leads to difficulty or occasionally failure during the automated mandrel loading operation. A mandrel clearance of at least 0.100in was maintained for all passes.

The two drawing speeds were selected with consideration given to production time and machine and process limitations. The draw bench which was used in the research had a maximum speed of 260ft/min. Furthermore, as previously mentioned the tubing underwent a multistep chemical process in order to apply an industrial soap lubricant before cold drawing. As part of this process there is a potential for varying levels of lubricant along the axial length of the tubing. These changes in lubricant can lead to inconsistent performance when attempting to draw tubing at the maximum speed. Chatter, or the elastic response of the mandrel rod due to varying friction conditions encountered by the mandrel, can result [10]. Figure 3-6 depicts the mechanical diagram of the drawing process with a fixed rod and shows how varying friction can lead to oscillation of the mandrel rod.

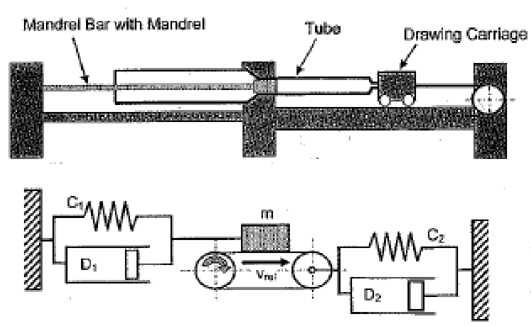


Figure 3-6: Mechanical Diagram of Drawing Using a Fixed Mandrel [10]

This oscillation leads to inconsistencies in wall thickness resulting in unacceptable tubing. In order to reduce the chances of chatter occurring and thus remove the quality of the lubricant application as a variable a maximum speed of 150ft/min was chosen based on past experiences. The minimum speed of 50ft/min was selected so that a wide range of drawing speed could be examined while still maintaining an acceptable production rate.

A total of 256 tubes were available for use. The 256 pieces were divided into 32 eight piece groups with each group representing one combination of variables from the experiment matrix previously presented. All eight pieces of a group were drawn and allowed to air cool to ambient temperature before any measurements were taken. Both the outer and inner surfaces were cleaned with an aerosol contact cleaner to remove any remaining lubricant film. Measurements were taken approximately 6in from the non-pointed tube end and at 120° intervals around the tube circumference as shown in Figure 3-7.

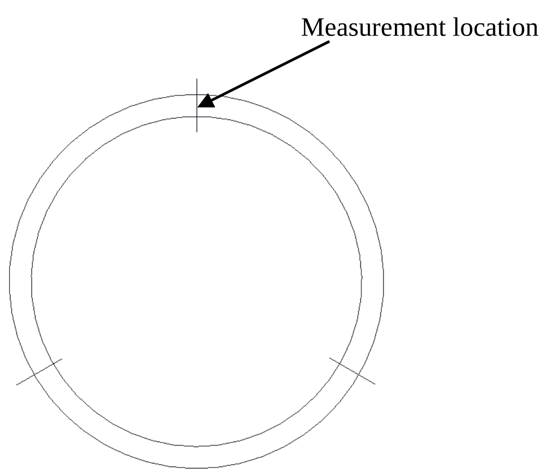


Figure 3-7: Circumferential Measurement Locations

Outer diameter measurements were taken with 2-3in and 3-4in series 103 Mitutoyo flat anvil micrometers; wall thickness measurements were taken with a 0-1in series 115 Mitutoyo ball and anvil micrometer. All micrometers were capable of measuring to 0.0001in with the use of a vernier scale. Calibration of the micrometers was checked with a certified gauge block before use, Figure 3-8 shows the micrometers used for outer diameter and wall thickness measurements.

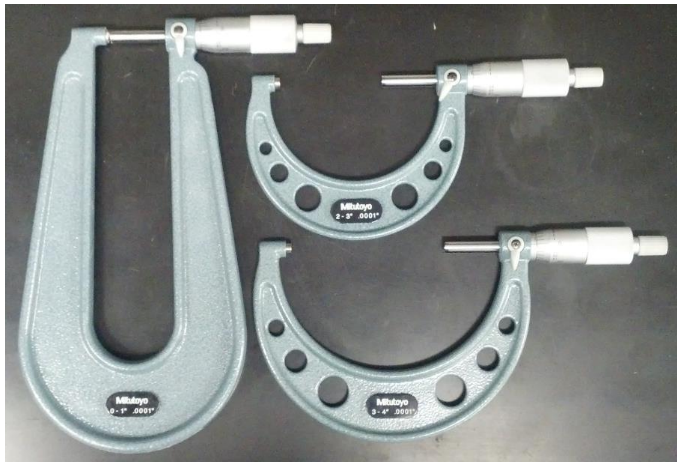


Figure 3-8: Micrometers Used for Measurements

Outer diameter and wall thickness measurements were tabulated and the minimum, maximum, and average values were determined along with the standard deviation. The deviation from the target outer diameter and wall thickness was then determined. The minimum, maximum, and average of the deviation values were determined based on the absolute value of the deviations. All outer diameter and wall thickness measurements are given in Appendix A.

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Introduction

There are two major characteristics of importance concerning dimensions of cold drawn tubing:

1. Dimensional consistency
2. Deviation from expected dimensions

Correlation of the expected as drawn dimensions with controllable process variables would allow less out of specification material to be produced at the start of a production run. Knowledge of the effects of process variables on the dimensional consistency of a given production run would allow for process controls to be implemented which improve the dimensional process capability.

In order to determine the effects of die angle, draw speed, and percent area reduction on these two characteristics, measurement data was tabulated for each combination of variables and the minimum, maximum, average, and standard deviation were determined in order to evaluate the consistency of the outer diameter and wall thickness of the drawn tubing. Additionally, the measurements were compared to the target outer diameter and wall thickness in order to determine the effects on the expected dimensions. The target outer diameter was simply the inner diameter of the working surface of the die nib. The target wall thickness was one half the difference between the die nib inner diameter and mandrel nib outer diameter. The minimum, maximum, average, and standard deviation of the difference between the actual measurements and the target measurements was determined based on the absolute values.

4.2 Experimental Results

As discussed in chapter 3, there were 32 unique test setups based upon die angle, area reduction, and draw speed. Even allocation of the available 256 tubes resulted in eight tubes being drawn in each unique test with three measurements taken for each tube; thus the averages and standard deviations shown in tables 4-1 through 4-8 are for a sample size of 24.

Table 4-1 shows the results for 15.45% area reduction for all die angles with a draw speed of 50ft/min.

			Die Angle			
			10°	15°	20°	25°
Outer Diameter	As Drawn	Minimum	3.2520	3.2520	3.2510	3.2510
		Maximum	3.2540	3.2560	3.2540	3.2540
		Average	3.2533	3.2534	3.2524	3.2526
		Std Dev	0.0006	0.0009	0.0011	0.0007
	Deviation from Target	Minimum	0.0020	0.0020	0.0010	0.0010
		Maximum	0.0040	0.0060	0.0040	0.0040
		Average	0.0033	0.0034	0.0024	0.0026
		Std Dev	0.0006	0.0009	0.0011	0.0007
Wall Thickness	As Drawn	Minimum	0.2315	0.2310	0.2305	0.2310
		Maximum	0.2340	0.2340	0.2335	0.2340
		Average	0.2325	0.2329	0.2320	0.2321
		Std Dev	0.0007	0.0008	0.0008	0.0007
	Deviation from Target	Minimum	0.0015	0.0010	0.0005	0.0010
		Maximum	0.0040	0.0040	0.0035	0.0040
		Average	0.0025	0.0029	0.0020	0.0021
		Std Dev	0.0007	0.0008	0.0008	0.0007

Table 4-1: 15.45% Area Reduction, 50ft/min Draw Speed

It was observed that the 10° die exhibited the lowest standard deviation for outer diameter measurements while both the 10° and 25° dies showed the lowest standard deviation for wall thickness measurements. The 20° die exhibited the highest standard deviation for outer diameter measurements. The 15° and 20° dies showed the highest standard deviation for wall thickness measurements. The 20° die also displayed the lowest average deviation from the target outer diameter and wall thickness dimensions. Table 4-2 shows the results for 15.45% area reduction with a draw speed of 150ft/min.

			Die Angle			
			10°	15°	20°	25°
Outer Diameter	As Drawn	Minimum	3.2540	3.2520	3.2515	3.2520
		Maximum	3.2550	3.2560	3.2560	3.2550
		Average	3.2545	3.2541	3.2533	3.2533
		Std Dev	0.0005	0.0010	0.0012	0.0008
	Deviation from Target	Minimum	0.0040	0.0020	0.0015	0.0020
		Maximum	0.0050	0.0060	0.0060	0.0050
		Average	0.0045	0.0041	0.0033	0.0033
		Std Dev	0.0005	0.0010	0.0012	0.0008
Wall Thickness	As Drawn	Minimum	0.2310	0.2310	0.2310	0.2310
		Maximum	0.2340	0.2340	0.2330	0.2335
		Average	0.2324	0.2323	0.2320	0.2320
		Std Dev	0.0008	0.0009	0.0005	0.0008
	Deviation from Target	Minimum	0.0010	0.0010	0.0010	0.0010
		Maximum	0.0040	0.0040	0.0030	0.0035
		Average	0.0024	0.0023	0.0020	0.0020
		Std Dev	0.0008	0.0009	0.0005	0.0008

Table 4-2: 15.45% Area Reduction, 150ft/min Draw Speed

The 10° die again displayed the lowest outer diameter standard deviation while the 20° die again resulted in the highest. For wall thickness measurements the 20° die showed the lowest standard deviation while the 15° die exhibited the highest result. Both the 20° and 25° dies offered the lowest average deviation from the target dimensions. Also of note was that at both draw speeds all measurements were greater than the target dimensions.

Table 4-3 shows the results for 20.19% area reduction at 50ft/min draw speed.

			Die Angle			
			10°	15°	20°	25°
Outer Diameter	As Drawn	Minimum	3.2020	3.2020	3.2000	3.2000
		Maximum	3.2050	3.2050	3.2040	3.2030
		Average	3.2028	3.2038	3.2019	3.2018
		Std Dev	0.0009	0.0007	0.0010	0.0006
	Deviation from Target	Minimum	0.0020	0.0020	0.0000	0.0000
		Maximum	0.0050	0.0050	0.0040	0.0030
		Average	0.0028	0.0038	0.0019	0.0018
		Std Dev	0.0009	0.0007	0.0010	0.0006
Wall Thickness	As Drawn	Minimum	0.2210	0.2200	0.2190	0.2190
		Maximum	0.2250	0.2250	0.2250	0.2250
		Average	0.2225	0.2236	0.2234	0.2220
		Std Dev	0.0010	0.0014	0.0015	0.0022
	Deviation from Target	Minimum	0.0010	0.0000	0.0000	0.0000
		Maximum	0.0050	0.0050	0.0050	0.0050
		Average	0.0025	0.0036	0.0035	0.0025
		Std Dev	0.0010	0.0014	0.0015	0.0022

Table 4-3: 20.19% Area Reduction, 50ft/min Draw Speed

At 20.19% area reduction the 25° die exhibited the lowest outer diameter standard deviation while the 10° die offered the lowest wall thickness standard deviation. The 20° and 25° die showed the highest standard deviations for outer diameter and wall thickness respectively. For outer diameter the 25° die showed the lowest average deviation from the target dimension. For wall thickness both the 10° and 25° dies showed the lowest average deviation from the target dimension. Table 4-4 gives the results at 150ft/min draw speed.

			Die Angle			
			10°	15°	20°	25°
Outer Diameter	As Drawn	Minimum	3.2030	3.2030	3.2020	3.2020
		Maximum	3.2040	3.2050	3.2040	3.2030
		Average	3.2035	3.2045	3.2027	3.2025
		Std Dev	0.0005	0.0006	0.0008	0.0005
	Deviation from Target	Minimum	0.0030	0.0030	0.0020	0.0020
		Maximum	0.0040	0.0050	0.0040	0.0030
		Average	0.0035	0.0045	0.0027	0.0025
		Std Dev	0.0005	0.0006	0.0008	0.0005
Wall Thickness	As Drawn	Minimum	0.2210	0.2200	0.2180	0.2180
		Maximum	0.2240	0.2250	0.2250	0.2250
		Average	0.2228	0.2233	0.2224	0.2224
		Std Dev	0.0010	0.0017	0.0023	0.0022
	Deviation from Target	Minimum	0.0010	0.0000	0.0000	0.0000
		Maximum	0.0040	0.0050	0.0050	0.0050
		Average	0.0028	0.0033	0.0027	0.0028
		Std Dev	0.0010	0.0017	0.0023	0.0022

Table 4-4: 20.19% Area Reduction, 150ft/min Draw Speed

At 150ft/min the 10° and 25° dies showed the lowest outer diameter standard deviation. The 10° die also showed the lowest wall thickness standard deviation. The 20° die exhibited the highest standard deviation for both outer diameter and wall thickness measurements. The 25° die also offered the lowest average deviation from the target outer diameter while the 20° die offered the lowest deviation from the target wall thickness. All outer diameter measurements were greater than or equal to the target dimension while the majority of wall thickness measurements were greater than or equal to the target dimension with measurements under the target wall thickness occurring for the 20° and 25° dies only.

Table 4-5 shows the results for 26.12% reduction with 50ft/min draw speed.

			Die Angle			
			10°	15°	20°	25°
Outer Diameter	As Drawn	Minimum	3.1010	3.1015	3.1010	3.0990
		Maximum	3.1020	3.1030	3.1025	3.1025
		Average	3.1016	3.1023	3.1017	3.1006
		Std Dev	0.0004	0.0006	0.0004	0.0008
	Deviation from Target	Minimum	0.0010	0.0015	0.0010	0.0000
		Maximum	0.0020	0.0030	0.0025	0.0025
		Average	0.0016	0.0023	0.0017	0.0008
		Std Dev	0.0004	0.0006	0.0004	0.0008
Wall Thickness	As Drawn	Minimum	0.2105	0.2115	0.2100	0.2100
		Maximum	0.2130	0.2130	0.2130	0.2130
		Average	0.2121	0.2123	0.2121	0.2119
		Std Dev	0.0006	0.0005	0.0008	0.0011
	Deviation from Target	Minimum	0.0005	0.0015	0.0000	0.0000
		Maximum	0.0030	0.0030	0.0030	0.0030
		Average	0.0021	0.0023	0.0021	0.0019
		Std Dev	0.0006	0.0005	0.0008	0.0011

Table 4-5: 26.12% Area Reduction, 50ft/min Draw Speed

The 10° and 20° dies displayed the lowest outer diameter standard deviation while the 15° die displayed the lowest wall thickness standard deviation. The 25° die offered the highest outer diameter and wall thickness standard deviation. The 25° die showed the lowest average deviation from both the target outer diameter and wall thickness. Table 4-6 shows the results for 150ft/min draw speed.

			Die Angle			
			10°	15°	20°	25°
Outer Diameter	As Drawn	Minimum	3.1015	3.1020	3.1015	3.1000
		Maximum	3.1030	3.1040	3.1030	3.1020
		Average	3.1023	3.1028	3.1024	3.1013
		Std Dev	0.0004	0.0005	0.0005	0.0006
	Deviation from Target	Minimum	0.0015	0.0020	0.0015	0.0000
		Maximum	0.0030	0.0040	0.0030	0.0020
		Average	0.0023	0.0028	0.0024	0.0013
		Std Dev	0.0004	0.0005	0.0005	0.0006
Wall Thickness	As Drawn	Minimum	0.2110	0.2110	0.2105	0.2100
		Maximum	0.2130	0.2130	0.2135	0.2130
		Average	0.2120	0.2121	0.2122	0.2117
		Std Dev	0.0004	0.0007	0.0008	0.0010
	Deviation from Target	Minimum	0.0010	0.0010	0.0005	0.0000
		Maximum	0.0030	0.0030	0.0035	0.0030
		Average	0.0020	0.0021	0.0022	0.0017
		Std Dev	0.0004	0.0007	0.0008	0.0010

Table 4-6: 26.12% Area Reduction, 150ft/min Draw Speed

At 150ft/min the 10° die offered the lowest standard deviation for both outer diameter and wall thickness. The 25° die showed the highest standard deviation for both outer diameter and wall thickness. The 25° die also offered the lowest average deviation from both the target outer diameter and wall thickness. All wall thickness measurements for both draw speeds were either greater than or equal to the target dimension. The majority of outer diameter measurements were greater than or equal to the target dimension with measurements under the target outer diameter occurring for the 25° die only.

Table 4-7 shows the results for 34.87% area reduction and 50ft/min draw speed.

			Die Angle			
			10°	15°	20°	25°
Outer Diameter	As Drawn	Minimum	2.8725	2.8740	2.8725	2.8735
		Maximum	2.8755	2.8755	2.8745	2.8750
		Average	2.8739	2.8749	2.8737	2.8745
		Std Dev	0.0007	0.0004	0.0005	0.0005
	Deviation from Target	Minimum	0.0000	0.0000	0.0005	0.0000
		Maximum	0.0025	0.0010	0.0025	0.0015
		Average	0.0011	0.0003	0.0013	0.0005
		Std Dev	0.0007	0.0004	0.0005	0.0005
Wall Thickness	As Drawn	Minimum	0.2000	0.2005	0.2005	0.2005
		Maximum	0.2025	0.2030	0.2025	0.2025
		Average	0.2016	0.2018	0.2016	0.2018
		Std Dev	0.0007	0.0007	0.0006	0.0006
	Deviation from Target	Minimum	0.0000	0.0005	0.0005	0.0005
		Maximum	0.0025	0.0030	0.0025	0.0025
		Average	0.0016	0.0018	0.0016	0.0018
		Std Dev	0.0007	0.0007	0.0006	0.0006

Table 4-7: 34.87% Area Reduction, 50ft/min Draw Speed

The 15° die offered the lowest outer diameter standard deviation while the 20° and 25° dies showed the lowest wall thickness standard deviation. The 10° die exhibited the highest standard deviation for outer diameter. The 10° and 15° dies showed the highest standard deviation for wall thickness measurements. The 15° die showed the lowest deviation from the target outer diameter and both the 10° and 20° dies showed the lowest average wall thickness deviation. Table 4-8 shows the results for 150ft/min draw speed.

			Die Angle			
			10°	15°	20°	25°
Outer Diameter	As Drawn	Minimum	2.8735	2.8740	2.8740	2.8740
		Maximum	2.8750	2.8755	2.8750	2.8755
		Average	2.8744	2.8748	2.8745	2.8749
		Std Dev	0.0006	0.0004	0.0004	0.0003
	Deviation from Target	Minimum	0.0000	0.0000	0.0000	0.0000
		Maximum	0.0015	0.0010	0.0010	0.0010
		Average	0.0006	0.0003	0.0005	0.0002
		Std Dev	0.0006	0.0004	0.0004	0.0003
Wall Thickness	As Drawn	Minimum	0.2000	0.2005	0.2000	0.2005
		Maximum	0.2030	0.2030	0.2025	0.2030
		Average	0.2014	0.2019	0.2017	0.2024
		Std Dev	0.0006	0.0007	0.0006	0.0007
	Deviation from Target	Minimum	0.0000	0.0005	0.0000	0.0005
		Maximum	0.0030	0.0030	0.0025	0.0030
		Average	0.0014	0.0019	0.0017	0.0024
		Std Dev	0.0006	0.0007	0.0006	0.0007

Table 4-8: 34.87% Area Reduction, 150ft/min Draw Speed

The 25° die offered the lowest standard deviation for outer diameter measurements while both the 10° and 20° dies showed the lowest standard deviation for wall thickness. The 10° die showed the highest outer diameter standard deviation and the 15° and 25° dies showed the highest wall thickness standard deviation. The 25° die offered the lowest average deviation from the target outer diameter while the 10° die offered the lowest average deviation from the target wall thickness. It was also observed that the majority of outer diameter measurements were less than the target dimension while all wall thickness measurements were greater than or equal to the target dimension.

4.3 Analysis of Process Variable Effects on Dimensional Consistency

The experimental results shown in section 4.2 were also plotted to allow further examination of the effects of area reduction, draw speed, and die angle on the dimensional consistency. Figure 4-1 shows the variation of the outer diameter against the three investigated variables.

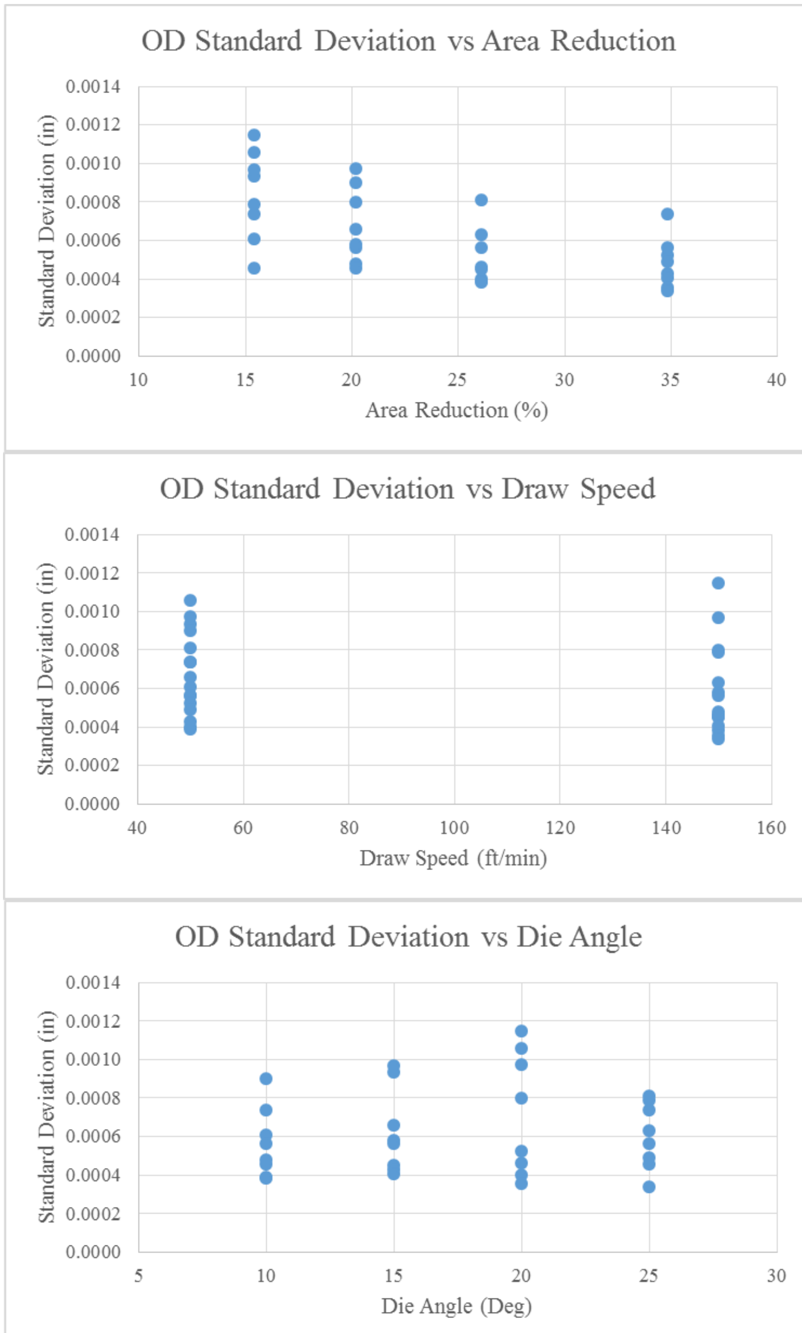


Figure 4-1: Process Variable Effects on Outer Diameter Standard Deviation

It was observed that the outer diameter standard deviation displayed an inverse relationship with percent area reduction. There was a positive relationship with die angle up to 20˚ and an inverse relationship thereafter; no strong correlation was observed with draw speed. Figure 4-2 shows the variation of the wall thickness standard deviation.

Figure 4-2: Process Variable Effects on Wall Thickness Standard Deviation

The wall thickness standard deviation showed a positive relationship with percent area reduction up to 20.19% and an inverse relationship thereafter. Again, no strong correlation with draw speed was observed. A weak positive correlation with die angle was noted.

In order to further examine the effects of die angle and percent area reduction the standard deviation variance with respect to percent area reduction was plotted in die angle groups. Figure 4-3 shows the variation of the outer diameter standard deviation with the effects of both die angle and percent area reduction.

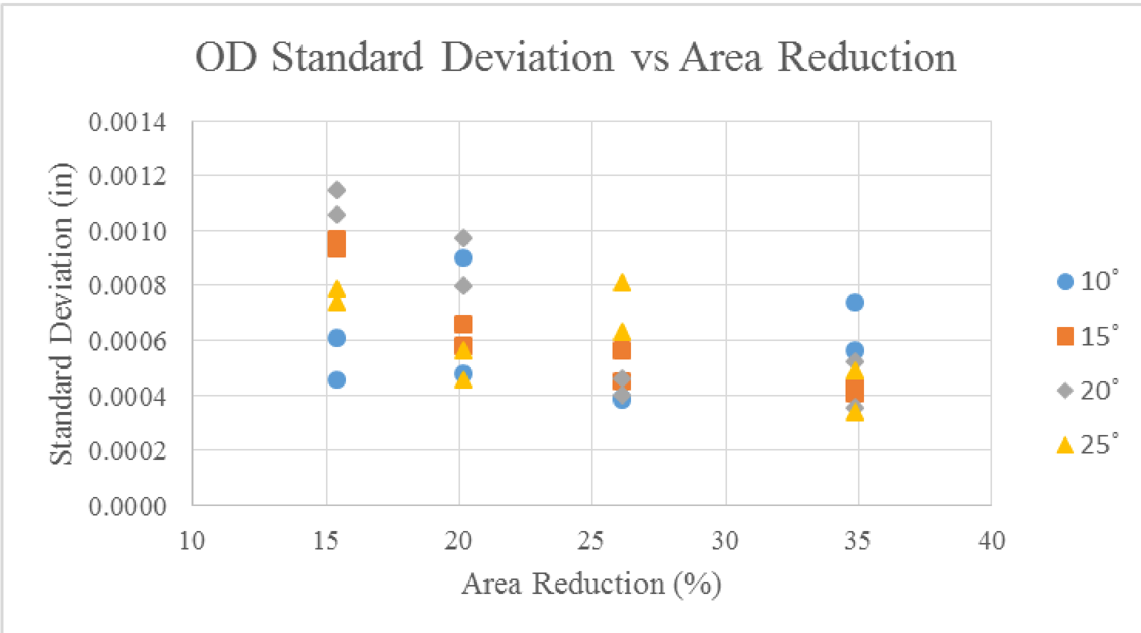


Figure 4-3: Combined Effects of Die Angle and Area Reduction on Outer Diameter Standard Deviation

A strong inverse relationship between outer diameter standard deviation and percent area reduction was observed for both the 15˚ and 20˚ dies. The 25˚ die showed a weaker inverse relationship while the 10˚ die showed a mostly flat overall relationship. Figure 4-4 shows the effects of die angle and percent area reduction on the wall thickness standard deviation.

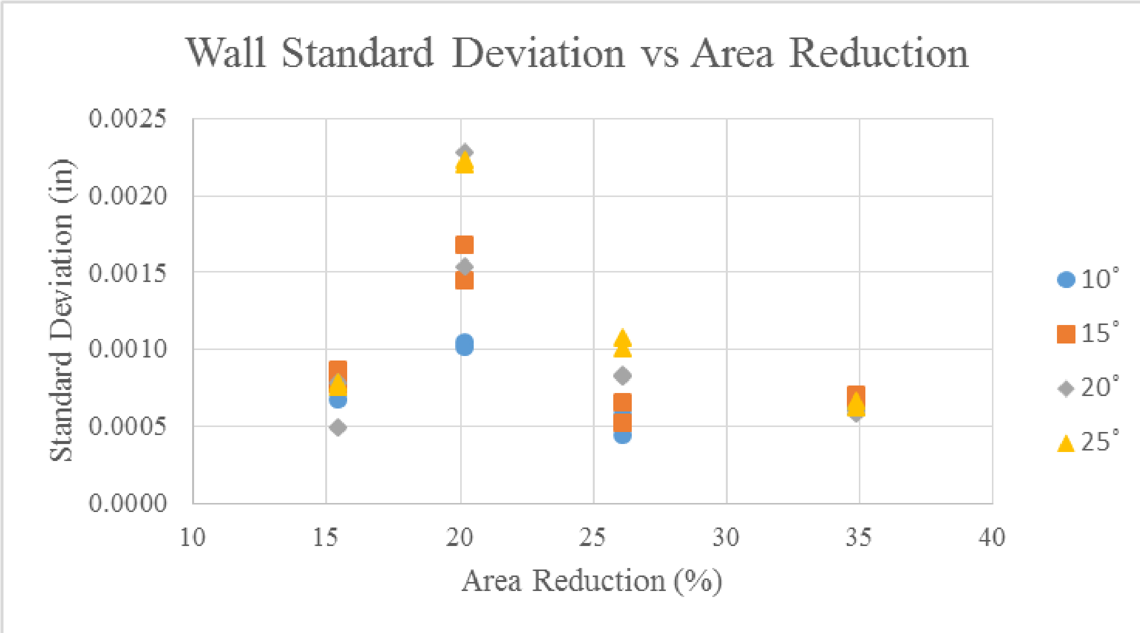


Figure 4-4: Combined Effects of Die Angle and Area Reduction on Wall Thickness Standard Deviation

All die angles showed a positive relationship between standard deviation and percent area reduction up to 20.19%. An inverse relationship was observed for higher percent area reductions.

4.4 Analysis of Process Variable Effects on Expected Dimensions

To determine the effects of percent area reduction, draw speed, and die angle on the deviation from the target dimensions the experimental data shown in section 4.2 was plotted against the three variables so any trends could be observed. Figure 4-5 shows the average outer diameter deviation vs the three process variables.

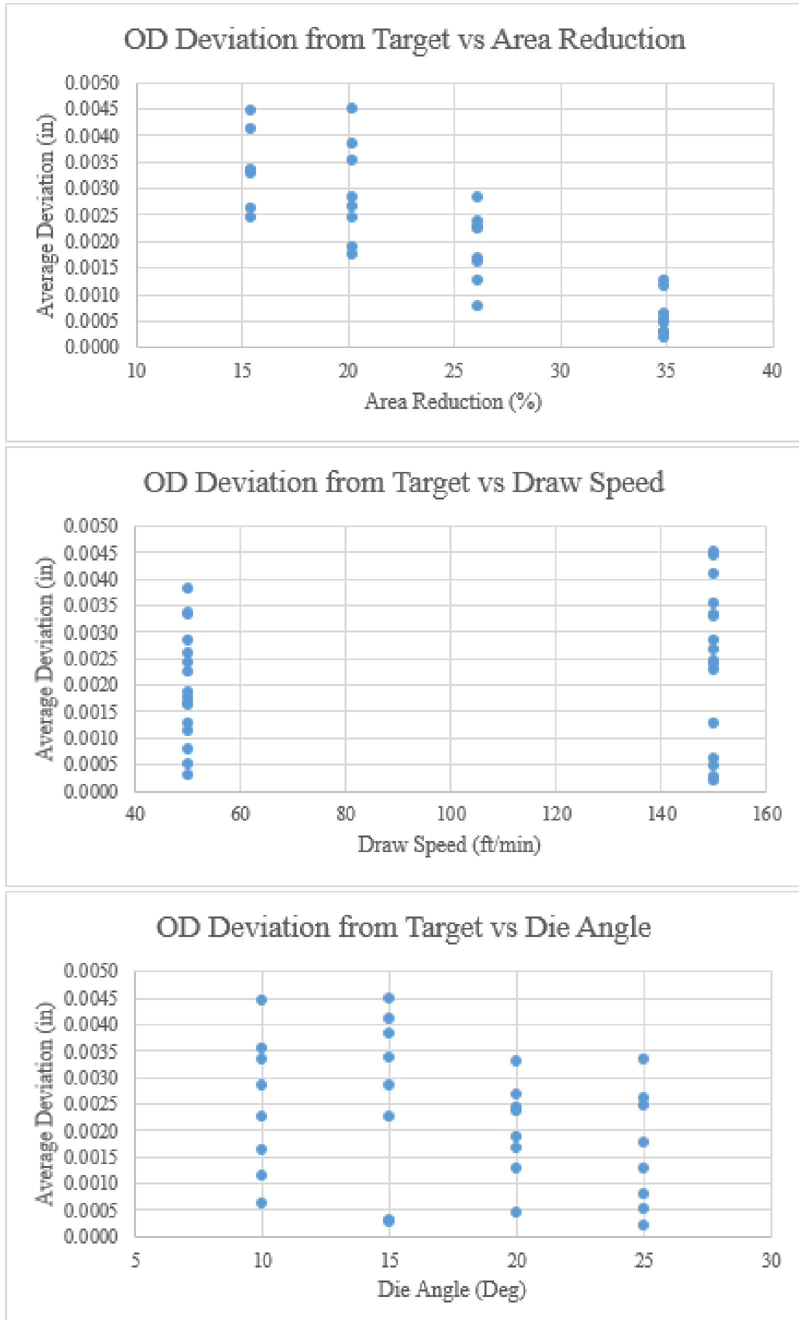


Figure 4-5: Process Variable Effects on Outer Diameter Average Deviation from Target

An inverse relationship between deviation from target dimensions and percent area reduction was observed. No strong correlation was observed with draw speed and a weak inverse relationship was observed with the die angle. Figure 4-6 shows the process variable effects on the wall thickness deviation from target dimensions.

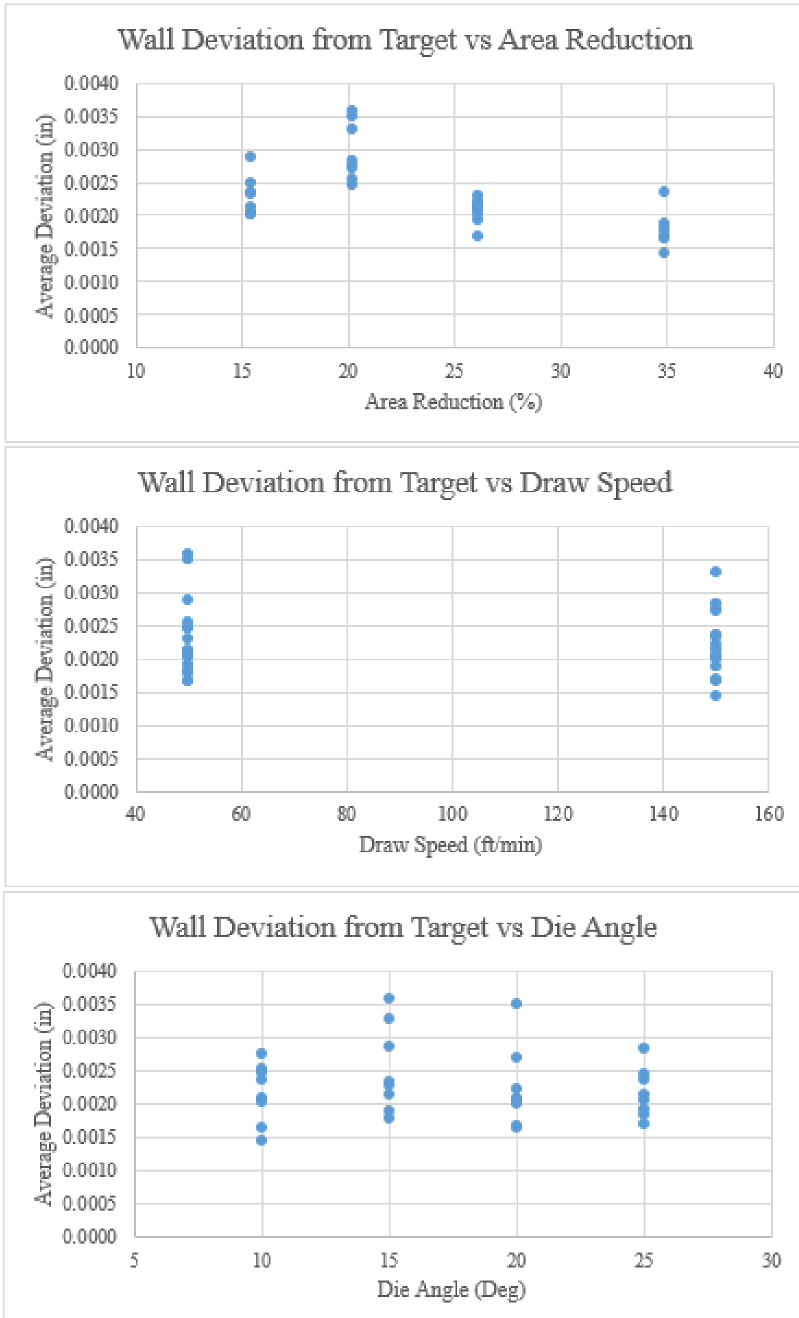


Figure 4-6: Process Variable Effects on Wall Thickness Average Deviation from Target

A positive relationship with percent area reduction was observed up to 20.19% with an inverse relationship at greater reductions. Die angle exhibited a weak positive relationship up to 20˚ with a weak inverse relationship thereafter. Again no strong correlation with draw speed was observed.

It was concluded that of the three process variables investigated, percent area reduction and die angle had the largest impact on the average deviation from target dimensions. In order to examine the combined effects of these two variables the data was plotted in die angle groups as in section 4.3. Figure 4-7 shows the combined effects of die angle and percent area reduction on the average outer diameter deviation from the target values.

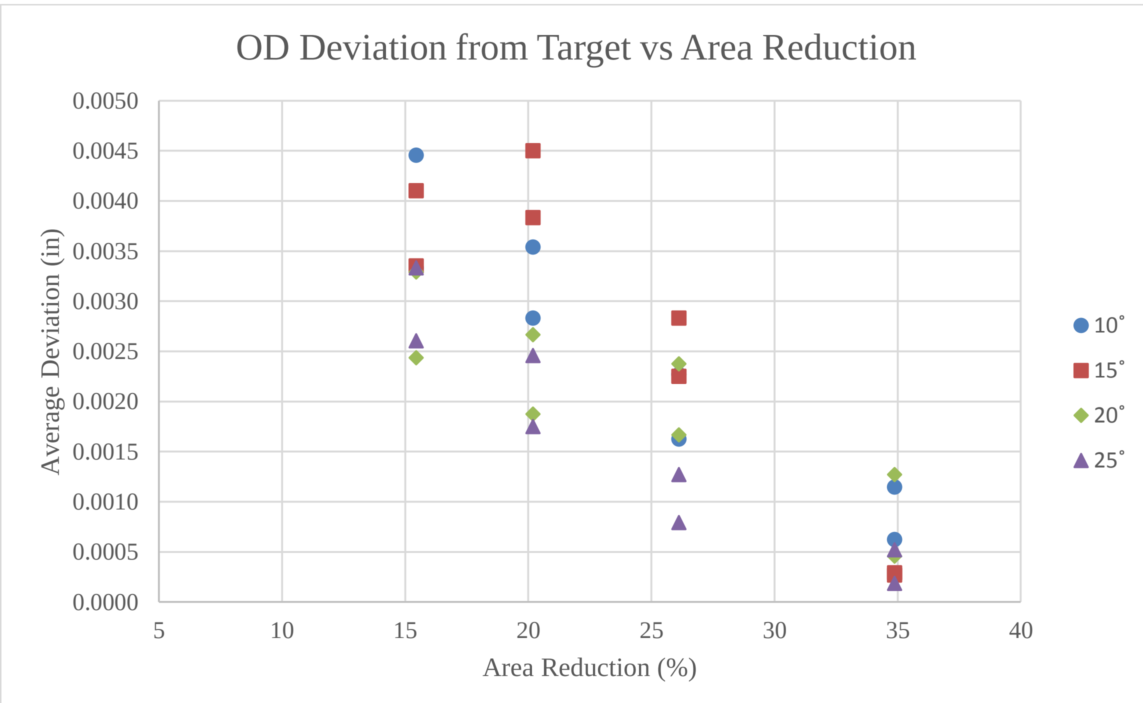


Figure 4-7: Combined Effects of Die Angle and Area Reduction on Outer Diameter Average Deviation from Target

A strong inverse relationship between average outer diameter deviation from target dimensions and percent area reduction was observed for all die angles. The strength of the relationship was observed to behave inversely with the die angle. Figure 4-8 shows the combined variable effects on the average wall thickness deviation from target.

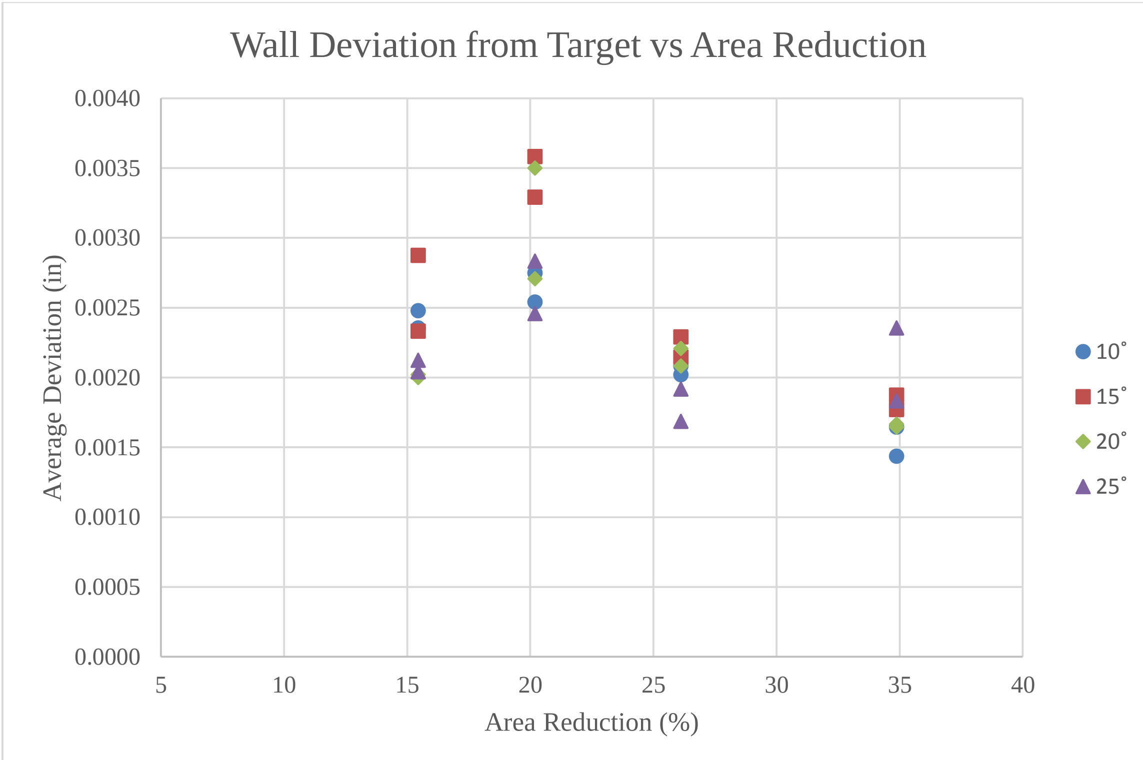
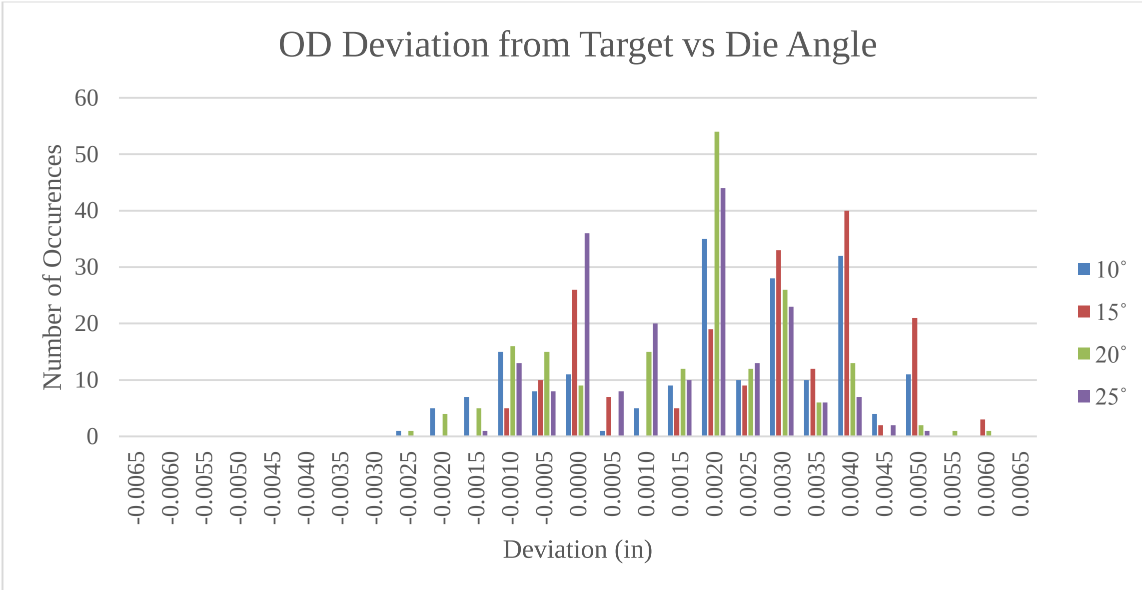


Figure 4-8: Combined Effects of Die Angle and Area Reduction on Wall Thickness Average Deviation from Target

With the exception of the 25˚ die a positive relationship was observed up to 20.19% area reduction with an inverse relationship thereafter. The 25˚ die exhibited a positive relationship up to 20.19% area reduction, an inverse relationship between 20.19% and 26.12%, and a weak positive relationship thereafter.

Of additional interest was the bias of the as drawn dimensions to be either greater than or less than the target dimensions. Figure 4-9 shows a histogram of all outer diameter and wall thickness deviations grouped by die angle for all 256 tubes.



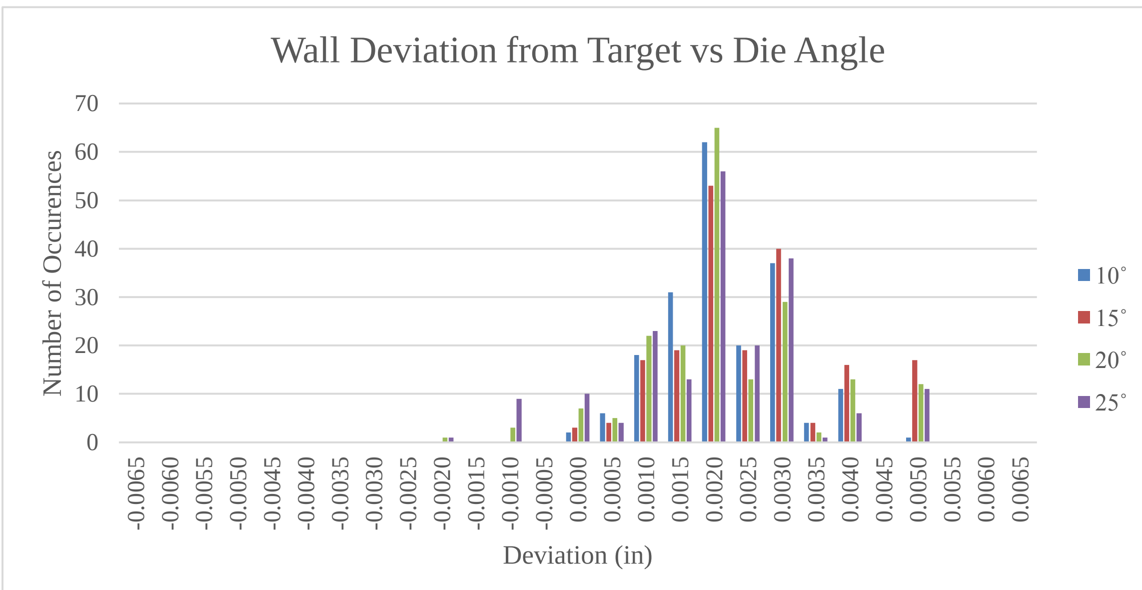
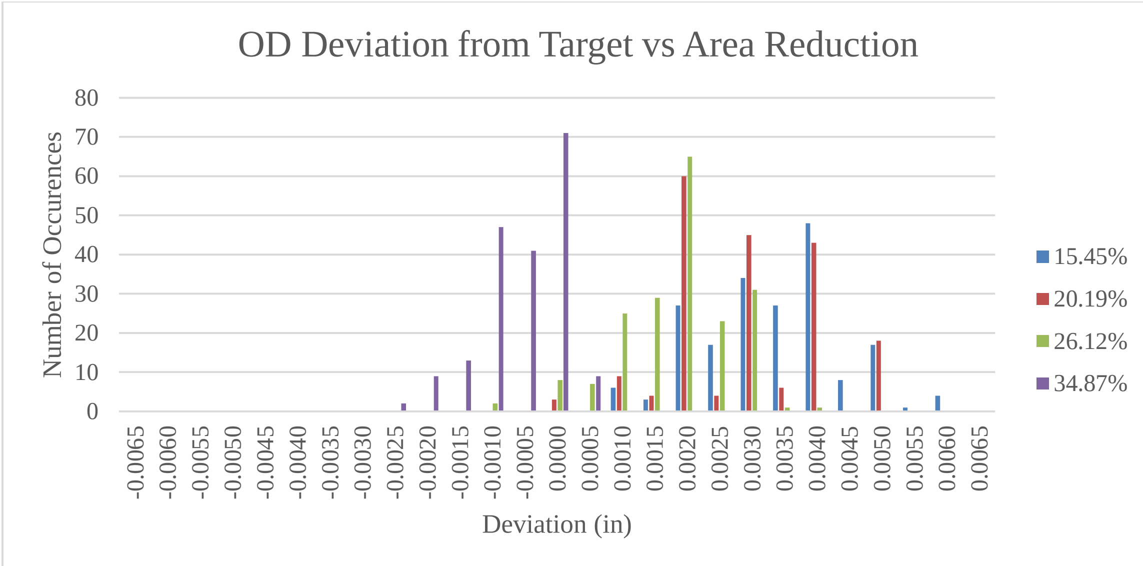


Figure 4-9: Die Angle Effect on Dimension Bias

When examined by die angle only, no strong trend was observed in the bias of the outer diameter dimensions. Wall thickness measurements showed a normal distribution for all die angles. Figure 4-10 shows a histogram of all outer diameter and wall thickness deviations grouped by percent area reduction for all 256 tubes.



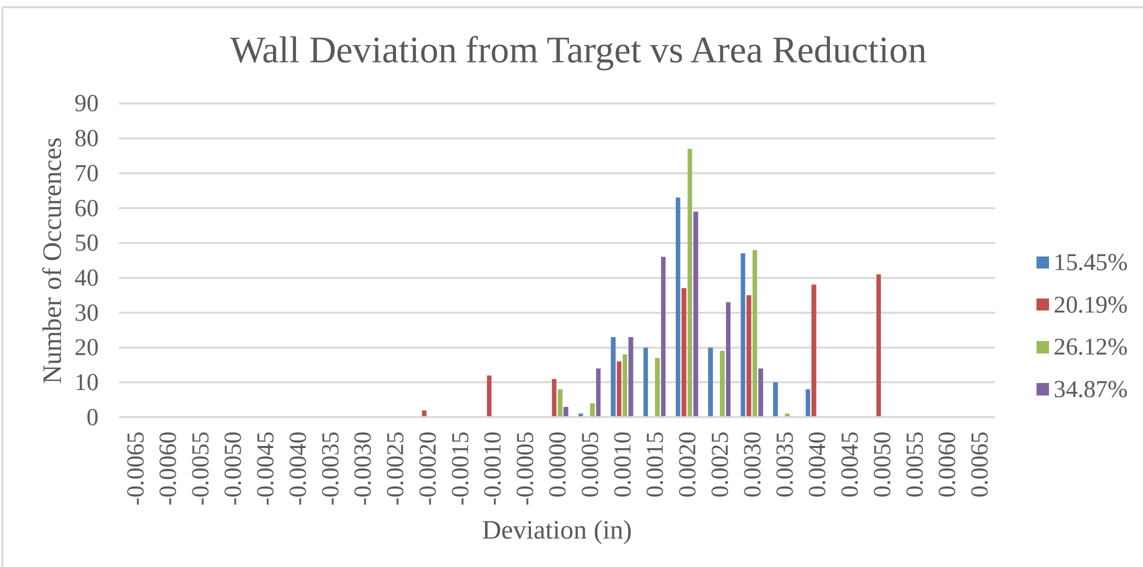


Figure 4-10: Area Reduction Effect on Dimension Bias

It was seen that for the outer diameter, as the percent area reduction increased the deviations became increasingly biased less than the target dimension. Wall thickness deviations again showed a normal distribution for all percent area reductions with the exception of 20.19%.

CHAPTER V

CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

The objective of this research was to determine the effects of die angle, draw speed, and percent area reduction on the as drawn dimensions of cold drawn steel tubing. The following conclusions can be drawn from the results obtained during this study:

- Outer diameter standard deviation varied inversely with percent area reduction for 15˚, 20˚, and 25˚ die angles. (Figure 4-3)
- Wall thickness standard deviation had a positive correlation with percent area reduction up to 20.19%. An inverse relationship occurred at higher percent area reductions. (Figure 4-4)
- Percent area reduction showed nearly no effect on both outer diameter and wall thickness standard deviation for a die angle of 10˚. (Figures 4-3 and 4-4)
- Outer diameter deviation from target dimensions varied inversely with percent area reduction. The trend was more pronounced at die angles of 10˚ and 15˚. (Figure 4-7)
- Wall thickness deviation from target dimensions varied inversely with percent area reduction above 20.19%. (Figure 4-8)
- Outer diameter measurements were biased less than the target dimensions with increasing percent area reductions. (Figure 4-10)
- Draw speeds between 50ft/min and 150ft/min did not have a major effect on as drawn dimensions. (Figures 4-1, 4-2, 4-5, and 4-6)

- Higher draw stress coupled with increased deformation likely negated any variation in the incoming material thus providing the negative correlations observed between both standard deviation and deviation from target with percent area reduction. (Figure 2.2)

5.2 Future Work

The experiments conducted in this study served to identify which process variables have a strong effect on as drawn dimensions. Conclusions were drawn based on the variable ranges investigated. Conducting further experiments which expand on the variable ranges investigated by this study would give more insight into process variable effects at extremes. Future work could include similar experiments in sinking, floating mandrel, and moving mandrel operations. Any effects of other material grades or drawing lubricants could also be explored.

This work focused solely on dimensional requirements; however DOM tubing is routinely purchased with mechanical requirements such as yield strength, tensile strength, hardness, maximum residual stresses, and grain size restrictions. Future studies could be conducted to examine the effects of process variables on these characteristics.

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APPENDIX A

MEASUREMENT DATA

15.45% Area Reduction

10˚ 50 FT/MIN		10˚ 150 FT/MIN		15˚ 50 FT/MIN		15˚ 150 FT/MIN	
OD	Wall	OD	Wall	OD	Wall	OD	Wall
3.2540	0.2330	3.2545	0.2320	3.2540	0.2320	3.2540	0.2330
3.2535	0.2315	3.2550	0.2330	3.2530	0.2330	3.2545	0.2320
3.2540	0.2340	3.2545	0.2325	3.2535	0.2310	3.2550	0.2320
3.2525	0.2325	3.2540	0.2330	3.2530	0.2330	3.2540	0.2320
3.2525	0.2315	3.2540	0.2315	3.2540	0.2330	3.2535	0.2310
3.2535	0.2330	3.2550	0.2330	3.2540	0.2320	3.2535	0.2340
3.2540	0.2325	3.2550	0.2320	3.2530	0.2340	3.2530	0.2335
3.2540	0.2330	3.2550	0.2320	3.2540	0.2330	3.2560	0.2330
3.2530	0.2325	3.2540	0.2335	3.2540	0.2340	3.2535	0.2320
3.2535	0.2320	3.2550	0.2320	3.2540	0.2320	3.2550	0.2330
3.2520	0.2320	3.2540	0.2320	3.2520	0.2320	3.2550	0.2330
3.2530	0.2315	3.2540	0.2315	3.2520	0.2330	3.2520	0.2315
3.2530	0.2315	3.2540	0.2330	3.2520	0.2340	3.2535	0.2310
3.2535	0.2330	3.2545	0.2330	3.2540	0.2330	3.2530	0.2320
3.2540	0.2335	3.2540	0.2325	3.2530	0.2320	3.2560	0.2330
3.2535	0.2320	3.2540	0.2310	3.2535	0.2330	3.2540	0.2320
3.2530	0.2325	3.2550	0.2310	3.2540	0.2320	3.2540	0.2335
3.2540	0.2320	3.2550	0.2315	3.2535	0.2330	3.2540	0.2325
3.2520	0.2335	3.2540	0.2320	3.2530	0.2330	3.2550	0.2315
3.2535	0.2325	3.2540	0.2310	3.2520	0.2335	3.2540	0.2310
3.2530	0.2320	3.2550	0.2330	3.2560	0.2340	3.2525	0.2330
3.2535	0.2325	3.2550	0.2330	3.2520	0.2330	3.2550	0.2325
3.2535	0.2330	3.2545	0.2335	3.2530	0.2330	3.2540	0.2310
3.2540	0.2325	3.2540	0.2340	3.2540	0.2335	3.2545	0.2330

20˚ 50 FT/MIN		20˚ 150 FT/MIN		25˚ 50 FT/MIN		25˚ 150 FT/MIN	
OD	Wall	OD	Wall	OD	Wall	OD	Wall
3.2530	0.2320	3.2530	0.2325	3.2535	0.2320	3.2525	0.2320
3.2535	0.2320	3.2535	0.2320	3.2530	0.2320	3.2535	0.2310
3.2530	0.2320	3.2530	0.2315	3.2530	0.2330	3.2550	0.2310
3.2520	0.2320	3.2525	0.2315	3.2525	0.2320	3.2530	0.2320
3.2515	0.2310	3.2550	0.2330	3.2520	0.2320	3.2530	0.2310
3.2520	0.2320	3.2525	0.2320	3.2525	0.2315	3.2540	0.2330
3.2510	0.2310	3.2520	0.2320	3.2530	0.2320	3.2535	0.2315
3.2520	0.2320	3.2540	0.2320	3.2530	0.2315	3.2545	0.2320
3.2525	0.2320	3.2525	0.2315	3.2535	0.2320	3.2520	0.2330
3.2535	0.2310	3.2540	0.2325	3.2520	0.2315	3.2530	0.2310
3.2520	0.2320	3.2525	0.2320	3.2520	0.2320	3.2540	0.2330
3.2540	0.2315	3.2530	0.2320	3.2530	0.2310	3.2535	0.2330
3.2510	0.2330	3.2535	0.2325	3.2540	0.2325	3.2540	0.2320
3.2540	0.2310	3.2525	0.2320	3.2520	0.2325	3.2530	0.2315
3.2540	0.2330	3.2550	0.2320	3.2525	0.2315	3.2520	0.2310
3.2535	0.2325	3.2535	0.2330	3.2510	0.2310	3.2530	0.2325
3.2510	0.2335	3.2520	0.2320	3.2520	0.2310	3.2535	0.2325
3.2530	0.2330	3.2530	0.2310	3.2530	0.2320	3.2540	0.2320
3.2520	0.2330	3.2530	0.2320	3.2515	0.2330	3.2525	0.2330
3.2510	0.2320	3.2560	0.2320	3.2530	0.2320	3.2525	0.2320
3.2520	0.2315	3.2515	0.2320	3.2540	0.2330	3.2540	0.2320
3.2540	0.2305	3.2555	0.2320	3.2520	0.2330	3.2530	0.2310
3.2520	0.2320	3.2520	0.2310	3.2525	0.2330	3.2525	0.2325
3.2510	0.2330	3.2540	0.2320	3.2520	0.2340	3.2545	0.2335

20.19% Area Reduction

10˚ 50 FT/MIN		10˚ 150 FT/MIN		15˚ 50 FT/MIN		15˚ 150 FT/MIN	
OD	Wall	OD	Wall	OD	Wall	OD	Wall
3.2030	0.2210	3.2040	0.2230	3.2035	0.2220	3.2050	0.2230
3.2030	0.2230	3.2040	0.2210	3.2040	0.2250	3.2040	0.2240
3.2050	0.2220	3.2030	0.2240	3.2040	0.2250	3.2050	0.2210
3.2030	0.2230	3.2030	0.2220	3.2040	0.2240	3.2040	0.2200
3.2020	0.2230	3.2040	0.2210	3.2050	0.2220	3.2050	0.2250
3.2050	0.2220	3.2030	0.2240	3.2040	0.2240	3.2040	0.2230
3.2020	0.2220	3.2030	0.2230	3.2035	0.2200	3.2050	0.2220
3.2030	0.2210	3.2040	0.2230	3.2040	0.2220	3.2040	0.2230
3.2020	0.2240	3.2040	0.2220	3.2040	0.2240	3.2050	0.2240
3.2030	0.2230	3.2030	0.2220	3.2020	0.2250	3.2040	0.2250

3.2040	0.2220	3.2040	0.2210	3.2030	0.2240	3.2050	0.2220
3.2020	0.2230	3.2030	0.2240	3.2030	0.2220	3.2040	0.2250
3.2020	0.2220	3.2035	0.2230	3.2040	0.2240	3.2040	0.2250
3.2020	0.2210	3.2030	0.2210	3.2040	0.2250	3.2050	0.2240
3.2030	0.2230	3.2040	0.2240	3.2030	0.2250	3.2050	0.2250
3.2030	0.2240	3.2035	0.2230	3.2040	0.2250	3.2040	0.2240
3.2030	0.2220	3.2040	0.2240	3.2050	0.2240	3.2050	0.2250
3.2030	0.2230	3.2040	0.2230	3.2040	0.2230	3.2030	0.2210
3.2020	0.2240	3.2030	0.2230	3.2040	0.2250	3.2050	0.2250
3.2030	0.2220	3.2040	0.2220	3.2040	0.2250	3.2050	0.2210
3.2020	0.2220	3.2040	0.2240	3.2050	0.2220	3.2040	0.2250
3.2040	0.2210	3.2030	0.2230	3.2035	0.2220	3.2050	0.2200
3.2020	0.2230	3.2040	0.2230	3.2040	0.2220	3.2050	0.2240
3.2020	0.2250	3.2030	0.2230	3.2035	0.2250	3.2040	0.2230

20˚ 50 FT/MIN		20˚ 150 FT/MIN		25˚ 50 FT/MIN		25˚ 150 FT/MIN	
OD	Wall	OD	Wall	OD	Wall	OD	Wall
3.2020	0.2240	3.2040	0.2240	3.2020	0.2240	3.2025	0.2250
3.2030	0.2250	3.2020	0.2250	3.2015	0.2190	3.2030	0.2200
3.2020	0.2240	3.2020	0.2200	3.2015	0.2230	3.2030	0.2240
3.2030	0.2250	3.2030	0.2220	3.2020	0.2240	3.2020	0.2220
3.2020	0.2240	3.2020	0.2250	3.2020	0.2190	3.2030	0.2190
3.2020	0.2220	3.2040	0.2200	3.2020	0.2240	3.2030	0.2250
3.2010	0.2250	3.2030	0.2240	3.2020	0.2230	3.2020	0.2210
3.2020	0.2230	3.2020	0.2250	3.2020	0.2230	3.2030	0.2250
3.2030	0.2230	3.2040	0.2240	3.2010	0.2200	3.2025	0.2180
3.2020	0.2240	3.2020	0.2180	3.2020	0.2190	3.2020	0.2250
3.2020	0.2240	3.2040	0.2210	3.2020	0.2250	3.2020	0.2220
3.2010	0.2200	3.2020	0.2210	3.2010	0.2220	3.2020	0.2230
3.2000	0.2230	3.2020	0.2250	3.2030	0.2220	3.2020	0.2190
3.2020	0.2230	3.2020	0.2220	3.2015	0.2190	3.2025	0.2220
3.2010	0.2230	3.2020	0.2250	3.2020	0.2250	3.2030	0.2220
3.2020	0.2250	3.2020	0.2200	3.2020	0.2210	3.2030	0.2220
3.2030	0.2220	3.2030	0.2190	3.2010	0.2250	3.2020	0.2210
3.2040	0.2250	3.2020	0.2240	3.2000	0.2190	3.2020	0.2250
3.2010	0.2240	3.2030	0.2200	3.2020	0.2190	3.2020	0.2250
3.2010	0.2240	3.2030	0.2190	3.2020	0.2220	3.2030	0.2220
3.2010	0.2220	3.2030	0.2240	3.2020	0.2200	3.2025	0.2230
3.2020	0.2250	3.2020	0.2250	3.2015	0.2220	3.2020	0.2240
3.2030	0.2240	3.2020	0.2220	3.2020	0.2250	3.2030	0.2190
3.2000	0.2190	3.2040	0.2230	3.2020	0.2230	3.2020	0.2250

26.12% Area Reduction

10˚ 50 FT/MIN		10˚ 150 FT/MIN		15˚ 50 FT/MIN		15˚ 150 FT/MIN	
OD	Wall	OD	Wall	OD	Wall	OD	Wall
3.1015	0.2120	3.1020	0.2125	3.1020	0.2130	3.1030	0.2120
3.1020	0.2130	3.1025	0.2120	3.1030	0.2120	3.1030	0.2115
3.1020	0.2120	3.1025	0.2115	3.1025	0.2120	3.1030	0.2120
3.1020	0.2120	3.1020	0.2115	3.1030	0.2130	3.1030	0.2120
3.1020	0.2115	3.1020	0.2125	3.1030	0.2115	3.1030	0.2110
3.1015	0.2120	3.1020	0.2120	3.1025	0.2120	3.1030	0.2125
3.1015	0.2105	3.1020	0.2115	3.1020	0.2130	3.1030	0.2130
3.1015	0.2120	3.1025	0.2120	3.1020	0.2120	3.1030	0.2120
3.1010	0.2130	3.1025	0.2120	3.1030	0.2130	3.1030	0.2120
3.1020	0.2130	3.1030	0.2120	3.1030	0.2120	3.1030	0.2125
3.1020	0.2125	3.1030	0.2120	3.1020	0.2125	3.1020	0.2130
3.1015	0.2115	3.1015	0.2120	3.1030	0.2120	3.1025	0.2125
3.1020	0.2120	3.1020	0.2125	3.1015	0.2125	3.1025	0.2120
3.1015	0.2125	3.1020	0.2130	3.1030	0.2120	3.1030	0.2130
3.1020	0.2120	3.1025	0.2120	3.1020	0.2120	3.1025	0.2130
3.1015	0.2120	3.1025	0.2120	3.1015	0.2130	3.1035	0.2110
3.1020	0.2120	3.1020	0.2120	3.1015	0.2120	3.1025	0.2120
3.1020	0.2120	3.1025	0.2115	3.1020	0.2125	3.1030	0.2125
3.1010	0.2130	3.1030	0.2120	3.1025	0.2115	3.1025	0.2110
3.1020	0.2120	3.1020	0.2120	3.1020	0.2130	3.1040	0.2130
3.1015	0.2125	3.1020	0.2120	3.1020	0.2120	3.1030	0.2120
3.1010	0.2115	3.1020	0.2110	3.1015	0.2120	3.1020	0.2115
3.1010	0.2115	3.1025	0.2130	3.1020	0.2130	3.1030	0.2130
3.1010	0.2120	3.1020	0.2120	3.1015	0.2115	3.1020	0.2115

20˚ 50 FT/MIN		20˚ 150 FT/MIN		25˚ 50 FT/MIN		25˚ 150 FT/MIN	
OD	Wall	OD	Wall	OD	Wall	OD	Wall
3.1015	0.2120	3.1030	0.2120	3.1025	0.2100	3.1020	0.2120
3.1020	0.2130	3.1020	0.2125	3.0990	0.2130	3.1005	0.2130
3.1015	0.2130	3.1030	0.2120	3.1010	0.2110	3.1005	0.2120
3.1020	0.2110	3.1020	0.2120	3.1000	0.2120	3.1020	0.2115
3.1020	0.2130	3.1030	0.2130	3.1010	0.2125	3.1020	0.2120
3.1020	0.2130	3.1020	0.2125	3.1010	0.2100	3.1000	0.2110
3.1020	0.2100	3.1030	0.2130	3.1005	0.2100	3.1020	0.2110
3.1015	0.2120	3.1020	0.2130	3.1010	0.2120	3.1005	0.2105
3.1020	0.2110	3.1020	0.2120	3.1010	0.2100	3.1010	0.2120
3.1020	0.2120	3.1025	0.2110	3.1010	0.2110	3.1005	0.2130
3.1015	0.2130	3.1025	0.2130	3.1000	0.2130	3.1015	0.2130

3.1015	0.2120	3.1015	0.2110	3.1005	0.2120	3.1020	0.2130
3.1015	0.2115	3.1020	0.2130	3.1000	0.2110	3.1010	0.2100
3.1015	0.2120	3.1025	0.2135	3.1000	0.2120	3.1020	0.2110
3.1025	0.2120	3.1030	0.2130	3.1010	0.2120	3.1010	0.2100
3.1020	0.2130	3.1025	0.2110	3.1010	0.2130	3.1010	0.2120
3.1020	0.2130	3.1020	0.2130	3.1000	0.2130	3.1010	0.2130
3.1020	0.2120	3.1030	0.2110	3.1000	0.2125	3.1020	0.2110
3.1015	0.2120	3.1020	0.2120	3.1015	0.2125	3.1005	0.2115
3.1015	0.2120	3.1020	0.2120	3.1000	0.2125	3.1015	0.2100
3.1010	0.2120	3.1020	0.2120	3.1010	0.2130	3.1020	0.2120
3.1010	0.2120	3.1020	0.2105	3.1020	0.2130	3.1015	0.2120
3.1010	0.2130	3.1025	0.2130	3.0990	0.2120	3.1010	0.2130
3.1010	0.2105	3.1030	0.2120	3.1010	0.2130	3.1015	0.2110

34.87% Area Reduction

10˚ 50 FT/MIN		10˚ 150 FT/MIN		15˚ 50 FT/MIN		15˚ 150 FT/MIN	
OD	Wall	OD	Wall	OD	Wall	OD	Wall
2.8750	0.2025	2.8750	0.2015	2.8750	0.2015	2.8750	0.2020
2.8745	0.2005	2.8735	0.2015	2.8745	0.2025	2.8750	0.2010
2.8750	0.2020	2.8740	0.2010	2.8745	0.2010	2.8755	0.2025
2.8755	0.2025	2.8750	0.2020	2.8745	0.2020	2.8745	0.2025
2.8740	0.2025	2.8750	0.2000	2.8745	0.2020	2.8750	0.2025
2.8740	0.2010	2.8740	0.2015	2.8750	0.2015	2.8750	0.2020
2.8725	0.2015	2.8740	0.2005	2.8740	0.2005	2.8740	0.2010
2.8740	0.2020	2.8740	0.2015	2.8740	0.2015	2.8755	0.2015
2.8730	0.2015	2.8735	0.2020	2.8745	0.2020	2.8750	0.2025
2.8735	0.2020	2.8750	0.2005	2.8750	0.2005	2.8750	0.2025
2.8730	0.2020	2.8750	0.2015	2.8755	0.2020	2.8745	0.2010
2.8740	0.2020	2.8745	0.2015	2.8750	0.2025	2.8750	0.2015
2.8735	0.2020	2.8750	0.2010	2.8750	0.2015	2.8750	0.2020
2.8740	0.2005	2.8740	0.2015	2.8750	0.2020	2.8745	0.2025
2.8740	0.2020	2.8740	0.2020	2.8755	0.2015	2.8750	0.2015
2.8735	0.2020	2.8750	0.2015	2.8750	0.2015	2.8740	0.2020
2.8740	0.2025	2.8735	0.2015	2.8750	0.2030	2.8745	0.2010
2.8745	0.2010	2.8745	0.2030	2.8750	0.2030	2.8750	0.2015
2.8745	0.2020	2.8740	0.2010	2.8750	0.2025	2.8750	0.2030
2.8745	0.2015	2.8745	0.2015	2.8755	0.2020	2.8750	0.2005
2.8740	0.2000	2.8750	0.2010	2.8755	0.2015	2.8750	0.2025
2.8730	0.2015	2.8750	0.2015	2.8750	0.2020	2.8750	0.2010
2.8730	0.2005	2.8735	0.2025	2.8755	0.2005	2.8740	0.2030
2.8730	0.2020	2.8745	0.2015	2.8750	0.2020	2.8745	0.2020

20˚ 50 FT/MIN		20˚ 150 FT/MIN		25˚ 50 FT/MIN		25˚ 150 FT/MIN	
OD	Wall	OD	Wall	OD	Wall	OD	Wall
2.8735	0.2015	2.8750	0.2015	2.8740	0.2010	2.8750	0.2015
2.8735	0.2025	2.8745	0.2015	2.8740	0.2005	2.8750	0.2015
2.8740	0.2010	2.8750	0.2010	2.8740	0.2005	2.8740	0.2025
2.8735	0.2020	2.8740	0.2015	2.8745	0.2025	2.8745	0.2020
2.8740	0.2020	2.8745	0.2010	2.8740	0.2010	2.8750	0.2020
2.8735	0.2015	2.8740	0.2010	2.8740	0.2020	2.8750	0.2025
2.8740	0.2005	2.8740	0.2015	2.8745	0.2020	2.8750	0.2030
2.8740	0.2015	2.8750	0.2025	2.8745	0.2020	2.8750	0.2020
2.8740	0.2020	2.8745	0.2015	2.8750	0.2020	2.8740	0.2020
2.8740	0.2005	2.8745	0.2015	2.8740	0.2020	2.8750	0.2030
2.8740	0.2020	2.8740	0.2020	2.8740	0.2020	2.8750	0.2005
2.8740	0.2010	2.8745	0.2015	2.8740	0.2015	2.8750	0.2025
2.8730	0.2010	2.8745	0.2020	2.8735	0.2015	2.8750	0.2030
2.8730	0.2010	2.8750	0.2015	2.8750	0.2020	2.8755	0.2030
2.8730	0.2015	2.8745	0.2025	2.8750	0.2025	2.8750	0.2025
2.8745	0.2025	2.8745	0.2025	2.8750	0.2020	2.8750	0.2030
2.8740	0.2020	2.8745	0.2020	2.8740	0.2020	2.8750	0.2030
2.8745	0.2020	2.8750	0.2010	2.8745	0.2020	2.8745	0.2020
2.8745	0.2015	2.8750	0.2020	2.8750	0.2025	2.8745	0.2020
2.8740	0.2025	2.8745	0.2000	2.8750	0.2025	2.8745	0.2030
2.8740	0.2015	2.8745	0.2025	2.8750	0.2025	2.8750	0.2030
2.8730	0.2020	2.8750	0.2020	2.8750	0.2010	2.8750	0.2025
2.8735	0.2020	2.8740	0.2020	2.8750	0.2025	2.8750	0.2030
2.8725	0.2020	2.8745	0.2020	2.8750	0.2020	2.8750	0.2015

VITA

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Completed the requirements for the Bachelor of Science in Mechanical Engineering and the Bachelor of Science in Aerospace Engineering at Oklahoma State University, Stillwater, Oklahoma in May, 2012.

Experience:

Worked as Technical Services Manager, Webco Industries, Sand Springs, OK (September 2014 to Present).

Worked as Mechanical Engineer, Webco Industries, Sand Springs, OK (May 2012 to September 2014).

Worked as Engineering Intern, New Product Development Center, OSU (November 2010 to May 2012).